CRYOGENICS PRIMER
CONTENTS

INTRODUCTION

This book is based on Bill Noe's Cryo 101 HyperCard program.

The word cryogenics means the science and art of producing cold(Scurlock 1). This is a simple definition and doesn't adequately describe its most frequent process, liquefying gasses.

This manual will cover what an Operator should generally know about cryogenics in order to operate the systems. History and other information will be added to round an Operator's overall knowledge.

If you are interested in further readings on cryogenics, please refer to the books used to create this document listed on the bibliography page.

DEFINITION

Cryogenics — how cold is cold?

"The cryogenic state has been described not as a fixed or definite temperature, but as a realm that begins below -150°C (-238°F)."

To an engineer, designing a cryogenic system, these temperatures present another problem:

> "[Below -150°C] the effects and reactions on system materials and components become important design considerations."

> The most significant consideration is the effect on carbon steel at cold temperatures. This material becomes brittle and can fail due to fracture. (from introduction, *Cryogenics Desks Guide*)

HISTORY

In the 1860's, research into the theories of cryogenics identified the concepts of phase separation and critical phenomena. These concepts were identified before gas liquefaction was accomplished. This early research discovered that "common gasses such as O_2 and N_2 have similar behavior when cooled to temperatures near their critical points"(Van Sciver, P3).

By 1877 Cailletet in France and Pictet in Switzerland were both liquefying oxygen. Their work proved that when permanent gases neared the gas's boiling point both liquid and vapor coexisted. Further, Pictet's process of cascade cooling and heat exchanging is today's preferred method of efficient refrigeration systems(Van Sciver, P4).

In 1892, Dewar developed a storage container that "consisted of a glass double-walled vacuum vessel with inner walls silvered to reduce radiation heat transfer"(Van Sciver, P4). An early schematic of a helium storage vessel showed that he used liquid nitrogen to further block thermal radiation.

The practical theory behind mechanical refrigeration came from a 28-year-old professor by the name of Carl von Linde. In 1870 Linde published a paper entitled, "The use of mechanical methods for the extraction of heat at low temperature." The Austrian brewery put his refrigeration designs to use immediately. Over the next eleven years a company he headed produced 1000 commercial refrigeration units. Linde continued to study the principles of thermodynamics and the work of Thomson and Joule. In 1895 Linde invented the first continuous process for air liquefaction, which allowed for the generation of bulk quantities of liquid oxygen(Baker 217).

Linde's liquefaction process relied on high-pressure gas and the Joule-Thomson effect. Unfortunately this process had a high rate of energy consumption.

In 1902, the French scientist George Claude developed a piston expansion engine that liquefied air by exporting mechanical work. This process was much more energy efficient and worked at lower pressures. L'Air Liquide was founded to exploit this process. Later, the American branch of this company changed its name to Airco(Baker 212-223).

TEMPERATURE

According to Webster's Dictionary, temperature is "the degree of hotness or coldness of anything, usually as measured on a thermometer." The question is, what scale does that thermometer use?

In the early years of cryogenic research, the establishment of an accurate, reliable and reproducible temperature scale was no easy matter(Scurlock 484). Early scales were assigned arbitrary numerical values to represent coordinate states of temperature values. Laboratories developed their own scales according to the fixed point of various materials. The fixed point they used depended on the substance they were studying.

What's a fixed point? A fixed point is a specific temperature for a specific material based on the material's triple point. The standard fixed point used in modern thermodynamics is the triple point of water, which is 273.16 °K.

What's a triple point? First let's describe phase equilibrium: phase equilibrium is the one temperature where a material coexists in either its solid and liquid form (melting point) or its liquid and vapor form (boiling point) with no phase exchange. Therefore, the triple point is where the solid, liquid, and vapor coexist in equilibrium. There is only one temperature and pressure where the triple point of a particular substance is possible.

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Anders **Celsius** (1701-1744), a Swedish astronomer and inventor, designed a thermometer scale that made the freezing point of water 0°, and the boiling point 100°C.

Celsius	
-273.16°C	Absolute zero
0°C	Triple point of water
100°C	Boiling point of water

Gabriel **Fahrenheit** (1686-1736), a German physicist who designated the scale which uses 32°F as the freezing point of water and 212°F as the boiling point.

Fahrenheit	
-459.67°F	Absolute zero
32°F	Triple point of water
212°F	Boiling point of water

William John MacQuorn **Rankine** (1820-1872), a Scottish physicist who designated an absolute temperature scale where the measurement interval equals a Fahrenheit degree, but his 0° point is equal to -459.67°F. According to this scale, the freezing point of water is 491.67°R.

Rankine	
0°R	Absolute zero
491.68°R	Triple point of water
672°R	Boiling point of water

William Thomson **Kelvin** (1824-1907), a British physicist and mathematician who designated a scale of thermodynamic temperature that uses absolute zero as its beginning point, but is not referenced to a substance. Room temperature is ~ 300°K.

Kelvin	
0°K	Absolute zero
273.16°K	Triple point of water
373.14°K	Boiling point of water

TEMPERATURE SCALE

In thermodynamic terms, the more interesting range of temperature for cryogenics is that from zero to 100° Kelvin. As you will see in future chapters, there is a direct relationship between absolute zero and entropy. (Entropy must be reduced to produce low temperatures.) The third law of thermodynamics says that absolute zero can't be reached. It's obvious, then, that the closer we come to absolute zero "the more difficult it is to obtain a unit temperature decrease"(Van Sciver 2). A linear scale won't represent this fundamental fact, a logarithmic scale would be more meaningful.

CONVERSION FACTORS
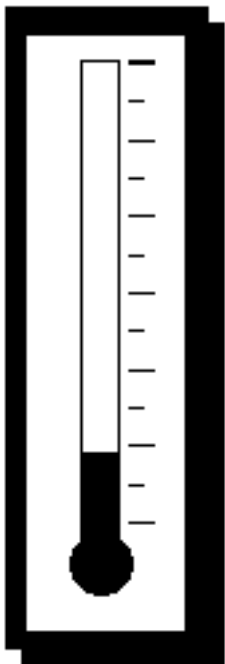
°K = °C+273. 15

°K= (5/9) (°F+459.67)

°K = (5/9) °R

°C = (5/9) (°F-32)

°C = °K-273.15

Example

°C = (5/9) (°F-32)
°C = (5/9) (70°F-32)
°C = 5/9 * 38
°C = 21.11

°K = °C+273.15
°K = 21.11 + 273.15
°K = 294.26

ABSOLUTE ZERO

Absolute zero **can not** be reached — that is the third law of thermodynamics. Both Nernst and Einstein confirmed this theory originally stated by the Carnot principle. Further, according to Sears, it would be wrong to say that all molecular activity stops at absolute zero, "Rather, at absolute zero the system has its minimum possible total energy (kinetic plus potential), although this minimum amount is in general not zero"(Sears 347). A further explanation of the three law of thermodynamics, the Carnot principle, and absolute zero can be found in the section on **Thermodynamic Laws**.

TYPICAL CRYOGENIC FLUIDS

CHANGES OF STATE

When a substance changes state, its molecules do not change, only their relation to each other. **Solid-state** molecules are free to move, but are kept in a rigid pattern by "tethers" of mutual attraction which cause them to form crystals. The molecules of **Melting** and **subliming** substances both need an extra dose of energy (**latent heat**) to break their attraction tethers. Liquid surface tension is a barrier caused by the unequal pull on molecules at the surface by the molecules inside the liquid. The **evaporation** and **condensation** of individual molecules go on at the same time, but the net effect is usually one or the other — evaporation

or condensation. With **saturation** in a closed vessel, molecules reentering the liquid equal those leaving the liquid as long as temperature is kept constant. Boiling (bubbles forming) in an open vessel takes place when the vapor pressure is equal to or greater than the external pressure.

GAS LAWS

Except near their condensing points, most gases follow these rules:

1. For a given pressure, gas expands in exact proportion to absolute temperature.
2. For a given volume the absolute pressure of a gas varies in exact proportion to the absolute temperature.
3. For a given temperature, the volume of a given weight of gas varies inversely to the absolute pressure.

These three rules can be summed up in one formula: $P \times V = k \times T$.

P = absolute pressure (lb. per sq. in.)
V = specific volume (cu. ft. per lb.)
T = absolute temperature (degree. F plus 460)
k = 10.7 divided by molecular weight of gas (k for air equals 0.37)

NITROGEN

Liquid nitrogen is inert, colorless, odorless, noncorrosive, extremely cold, and nonflammable. The molecular symbol for nitrogen is N_2. Liquid nitrogen has an expansion ratio of 1 to 694. It can produce suffocation by diluting the concentration of oxygen in the air below levels necessary to support life.

Boiling Point @ 1 atm	77.32°K	-320.5°F	-195.8°C
Freezing Point @ 1 atm	83.4°K	-346.0°F	-210.0°C
Critical Temperature	126.1°K	-232.4°F	-146.9°C
Critical Pressure	493 psia (33.5 atm)		

ARGON

Liquid argon is inert, colorless, odorless, noncorrosive, extremely cold, and nonflammable. The molecular symbol for argon is Ar. Liquid argon has an expansion ratio of 1 to 840. It can produce suffocation by diluting the concentration of oxygen in the air below levels necessary to support life.

Boiling Point @ 1 atm	87.4°K	-297.6°F	-185.9°C
Freezing Point @ 1 atm	63.46°K	-308.9°F	-189.4°C
Critical Temperature	150.8°K	-188.4°F	-122.4°C
Critical Pressure	705 psia (48.0 atm)		

HELIUM

Liquid helium is inert, colorless, odorless, noncorrosive, extremely cold, and nonflammable. The molecular symbol for helium is He. Liquid helium has an expansion ratio of 1 to 700. It can produce suffocation by diluting the concentration of oxygen in the air below levels necessary to support life.

Boiling Point @ 1 atm	4.26°K	-452.1°F	-268.9°C
Freezing Point @ 1 atm	---------	-458.0°F	-272.2°C
Critical Temperature	5.2°K	-450.3°F	-268.0°C
Critical Pressure	33.2 psia (2.26 atm)		

HYDROGEN

Liquid hydrogen is highly flammable, colorless, odorless, noncorrosive, and extremely cold. The molecular symbol for hydrogen is H_2. It can produce suffocation by diluting the concentration of oxygen in the air below levels necessary to support life. Its explosive limits, when mixed with air, are 4% to 74%.

Boiling Point @ 1 atm	20.43°K	-423.0°F	-252.5°C
Freezing Point @ 1 atm	13.98°K	-431.4°F	-259.14°C
Critical Temperature	32.976°K	-399.9°F	
Critical Pressure	12.76 atm		

Compare the boiling point of R-22 refrigerant to the cryogenic fluids listed below.

Gas	Boiling Points	
R-22	-41.4°F	232.4°K
Argon	-297.6°F	87.40°K
Hydrogen	-423.0°F	20.43°K
Oxygen	-297.3°F	90.13°K
Nitrogen	-350.5°F	77.35°K
Helium	-452.1°F	4.26°K
Neon	-410.4°F	27.21°K

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ENERGY

The term energy is often used in reference to the capacity of doing work. In physics, the term specifically refers to the force required to displace a body a certain distance. (You will see that in Cryogenics the term energy is used in a slightly different way.)

The most commonly thought of unit of energy is the **watt**. A watt is not exclusively electrical, even though electrical power is measured in watts. (Power consumption of an incandescent light can also be expressed in horsepower.) A watt is a unit of power equal to about 1/746 horsepower (HP), or 1 HP is equal to 746 watts. The Research Department's satellite refrigerators require ~600 watts @ 4.2°K.

In normal refrigeration, British thermal units (BTU's) are the units used to describe the size or capacity of a refrigerator. A **BTU** is the energy needed to raise the temperature of 1 pound of water from 63°F to 64°F. A ton of refrigeration is based on the number of BTU's required to melt a ton of ice (or freeze a ton of water) in 24 hours (288,000 BTU). 1 ton of refrigeration equals 12,000 BTU/hr.

A **joule** is the most commonly used term in reference to units of work. The unit of force is the newton, which is the force that gives a standard kilogram an acceleration of 1m * s^{-2}. The unit of distance is the meter. A joule is equal to 1 *newton meter* (1 N * M). (To translate this into something a little more tangible, a joule is approximately equal to the energy produced by the friction of rubbing your thumb and forefinger together.)

The efficiency of a cryogenic system is dependent on its methods of energy transfer through the performance of work and the transfer of heat. These concepts will be further explained in the sections on **Refrigeration and Liquefaction Principles** and in **Expansion Engines**.

CONVERSION FACTORS

1 lb. = 453.6 gms.
1 cu. ft. = 28.316 liters = 7.481 gal.
1 gal. = .1337 cu. ft. = 3.785 liters =231 cu. in..
1 BTU = 1054.8 joules
1 watt = 3.413 BTU/hr.

Helium @ 70° F, 1 atm	Air @ 70° F,1 atm
1Kg = 213.23 cu. ft.	1 Kg = 29.42 cu. ft.
1g = .21323 cu. ft.	1g = .02942 cu. ft.
60 g/s = 12.7938 CFS	60 g/s = 1.7652 CFS
60 g/s = 767.628 CFM	60 g/s = 105.912 CFM

HEAT TRANSFER

There are three forms of heat transfer; **conduction**, **convection**, and **radiation**. Heat is always transferred from the higher temperature to the lower temperature. It is important to understand that there is no cold, only a lower level of heat. Think of it this way, the amount of heat in ice is lower than that in a cup of hot coffee.

> **Conduction**...when an object is warm on one end and cold at the other there is heat transfer from the warm end to the cold end. Heat transfer stops when equilibrium is reached. (Heat is CONDUCTED through the walls of a house or through the walls of a pipe.) The rate of conductive heat transfer is proportional to the temperature difference and to the thermal conductivity.

> **Convection**...when a fluid at one temperature flows over an object at a different temperature, heat transfer occurs. (Air blowing over a hot surface is an example of CONVECTION, as is water flowing over a hot surface.) The rate of convective heat transfer is proportional to the temperature difference, the velocity of the flow, and the type of fluid.

> **Radiation**...takes place without any medium. (As in solar RADIATION, or with heat radiating from a fire.) The rate of radiative heat transfer is proportional to the temperature difference and the emissivity of the surface. Emissivity is the relative ability of a surface to radiate energy (heat) as compared with that of an ideally black surface. It is also a ratio of how much heat is absorbed to the total radiation energy.

> Example: If you were to take a hot branding iron and touch it, the heat would burn your hand through **conduction**. If you placed your hand above the branding iron, you would feel the warmth of the iron carried by **convection** through the upward moving air currents. And finally, you could feel the hot iron's heat **radiation** by putting your hand along side or under the branding iron.

The major problem of any helium cryogenic system is that of heat leaks. There may be conduction up the heat exchanger and internals, or radiation heat leaks from various points between the refrigerator and the magnets. Heat leaks can be minimized by the use of **vacuum jackets** and **nitrogen shields**. These and other design techniques can significantly reduce heat leaks and their resulting draw on energy and lost efficiency.

ENTHALPY (HEAT)

An engineer will define enthalpy by the equation $H = U + PV$, where U is the internal energy, PV is the product of pressure and volume, and H is the enthalpy. It's common to hear an engineer explain that the change in enthalpy is a measure

of the heat absorbed by a system in a constant pressure process. More simply, you could call it a measure of the energy of a system per unit mass.

Operators might better concentrate on understanding the following three terms; **sensible** heat, **latent** heat, and **total** heat.

> **Sensible heat**... is a <u>change in temperature</u> of a substance <u>with no change in state</u>. Water, as it exists between 32°F and 212°F, represents sensible heat in the heating of 1 lb. of water. It takes approximately 180 BTU's to make this temperature change of 32°F to 212°F.

> **Latent heat**... is the heat required to <u>change the state</u> of a substance with <u>no change in temperature</u>. Water at 32°F represents the latent heat required to convert water to ice or ice to water. (The latent heat of fusion of 1 lb. of water is ~140 BTU's.) Water at 212°F represents the latent heat required to convert water to steam or steam to water. (The latent heat of vaporization of 1 lb. of water is ~970 BTU's.)

> **Total heat**... includes both latent heat and sensible heat. In this case it takes ~1290 BTU's to convert 1 lb. of ice to 1 lb. of steam at 14.7 psia. You can have ice colder than 32°F and steam hotter than 212°F, but that adds to the total BTU's. (For your information; 1290 BTU/hr = 378 watts.)

THERMODYNAMIC LAWS

A simple understanding of the three laws of thermodynamics would be useful and necessary for anyone working with cryogenic systems, but a simple explanation will leave much ground uncovered. However, here's an attempt:

1. The energy output of an engine, in the form of mechanical work, shall equal the difference between the energies absorbed and rejected in the form of heat.

2. No engine can have a thermal efficiency of 100%.

These first two laws are always taught in conjunction with each other. This is largely due to the fact that the first law denies the possibility of creating or destroying energy (work in equals work out), and the second law denies the possibility of utilizing energy in a particular way (you can't have the work out of an engine drive the work in of an engine, thereby creating a perpetual motion machine).

Why is this true? It is true because heat cannot be made to flow from a cold body to a hot body without the addition of work or energy. Here are some examples of the second law of thermodynamics at work:

- Heat always flows spontaneously from a hotter to a colder body.

- Gases always seep through an opening spontaneously from a region of high pressure to a region of low pressure.
- Gases left by themselves always tend to mix.
- Salt dissolves in water, but a salt solution does not separate by itself into pure salt and pure water.
- Rocks weather and crumble.
- Iron rusts. (Sears 342)

All these examples of irreversible processes express the one-sidedness of the second law of thermodynamics. (This is also referred to as **entropy**: a measure of the degree of disorder in a substance or a system: entropy always increases and available energy diminishes in a closed system, as in the universe.)

How is this applicable to cryogenics? The heat engine is reversed to act as a heat pump.
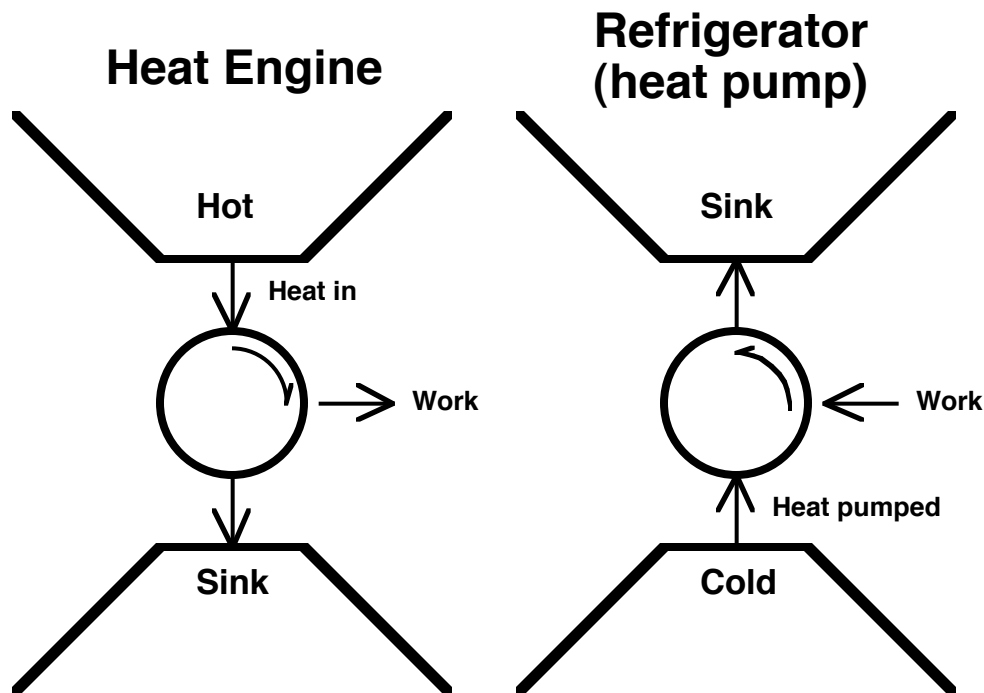
The heat pump absorbs heat at a low temperature, below ambient, and rejects the heat at a higher temperature into the environment through the absorption of work. Here's the important point: <u>work</u> is required to pump the heat from a low temperature to a higher environmental temperature(Scurlock 26).

> The first law demands that the difference between the heat and work for the two paths must be equal in magnitude but opposite in sign.

> The second law of thermodynamics is concerned with the conversion of heat into work and the efficiency with which this can take place(Van Sciver 10).

Carnot, a French physicist, developed a formula for expressing the efficiency of an ideal engine, that is, a theoretical engine that has no heat loss:

$$W/Q = T_E / T_L - 1$$

W/ Q shows the specific power ratio of <u>work</u> (**W**) performed in watts to <u>heat</u> pumped (**Q**) in watts, in relationship to the (**T_E**) <u>environment temperature</u> and the (**T_L**) <u>low temperature</u> required. If you add to this formula the efficiency of a real refrigerator, it will divide the quantity [**T_E / T_L -1**] by something less than a Carnot device. With this new formula you find that the energy required to reach the "absolute zero" of temperature is infinite. This result brings us to the third law of thermodynamics in regards to cryogenics:

3.   Absolute zero is unattainable(Scurlock 27, Van Sciver 13).

JOULE-THOMSON EFFECT

When air is compressed at room temperature, there is a reduction in its enthalpy, or heat content, the amount varying with pressure. On expanding the compressed air (or most any compressed gas) through a valve to atmospheric pressure there is a reduction in temperature, and in the steady state, this cooling is a function of the decrease in enthalpy during compression. By adding a heat exchanger between the compressor and the expansion valve, progressively lower temperatures are reached. With a sufficiently high pressure, and appropriate insulation, the air is liquefied. The cooling effect is due to the non-ideality of air — with an ideal gas no cooling would occur.

With some of the so-called permanent gases such as helium and hydrogen, there is an increase in enthalpy on compression at room temperature, and heating occurs on expansion through a valve. The gas must first be pre-cooled to a lower temperature before a cooling effect on expansion is achieved.

Joule-Thomson expansion is not thermodynamically reversible, and an increase in entropy occurs during expansion. This method of liquefaction was used in early refrigeration plants(Scurlock 181).

For the J-T method of cooling to work with helium, it is necessary to begin below the inversion curve, which implies an initial temperature below about 40°K.

The J-T valve performs an isenthalpic expansion of the high-pressure stream. Provided the inlet temperature is below the inversion curve, the J-T expansion can produce a two-phase mixture of liquid and vapor helium. An enthalpy balance between the incoming high-pressure stream and the two coexisting phases at ambient pressure (Van Sciver 289) determines the yield of the expansion stage.

MAKING LIQUID HELIUM

"Helium is the most difficult of all gases to liquefy because of its very low boiling point, 4.2°K, and its low inversion temperature for the JT effect, about 40°K. When liquefying helium for laboratory use, economy of power is seldom a consideration. The major expenses are for the complex machinery and for the human effort needed to operate it"(Scott 57). The JT effect spoken of here is the result of research by Joules and Thomson, which was just explained, and is the common way of referring to the Joule-Thomson Effect.

The helium atom is spherically symmetrical, and smaller than that of any other element. The only binding forces in the liquid are van der Waals forces, which arise from the fluctuating polarization charges induced in the electron shells of adjacent atoms. These weak attractive forces between electrically neutral atoms and molecules are weaker in helium than in all other substances, so the critical and boiling points of helium are the lowest of all(Wilkes 1).

There exists two isotopic forms of liquid helium used in most cryogenic research projects, liquid ^{3}He and ^{4}He. Both types of helium remain liquid to the lowest temperatures as long as they remain under their saturated vapor pressures(Wilkes 1).

Fermilab doesn't extract helium from the atmosphere. A contractor supplies the lab with tube trailers of ^{4}He.

For those interested, Fermilab uses a satellite refrigerator modeled after the CTI 1400 liquefier.

REFRIGERATION CYCLE

The refrigeration cycle shown here is a typical R-22 system. The compressor and thermal expansion valve are the boundaries for the high and low sides.

It's important to understand that a refrigerator is a heat engine that operates in reverse. Energy is transferred from a low level to high level, which is contrary to the spontaneous processes that occur in nature. To accomplish this transfer, an amount of work must be supplied dependent on the temperatures involved. Energy must be added to this workload to compensate for the inefficiencies inherent in heat transfer, inefficiencies that arise from heat exchange equipment and the irreversible behavior of compression or expansion equipment.

Some of the same principles used in this basic system apply to normal cryogenic refrigeration systems as well.

A BASIC SYSTEM
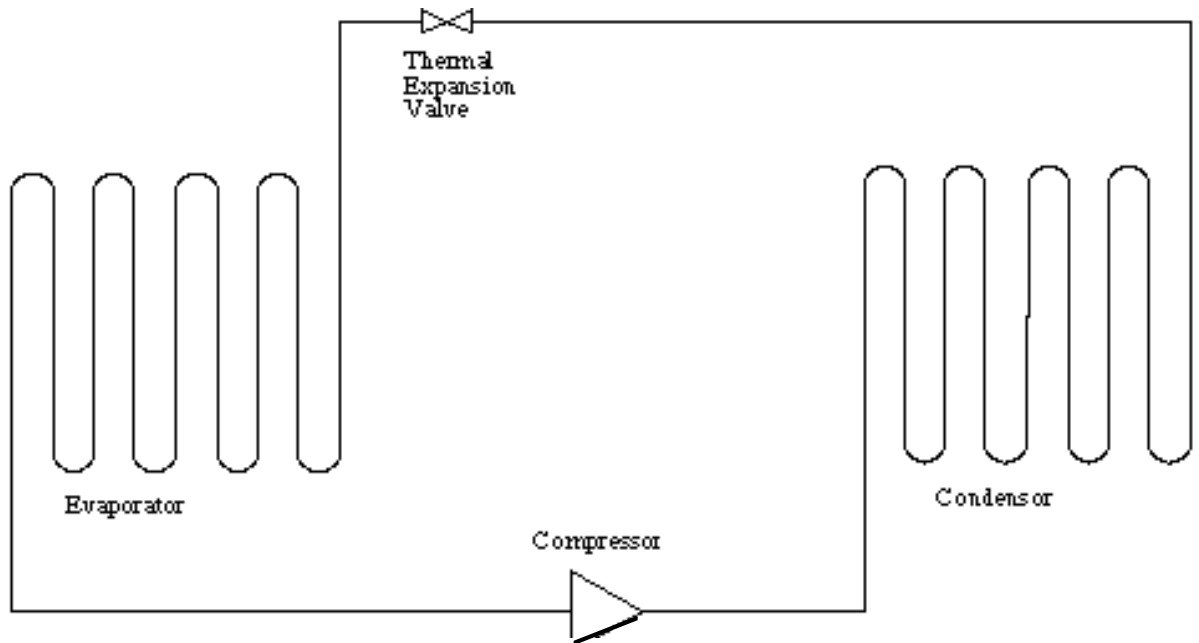
COMPRESSOR

The **compressor** takes low pressure, low temperature gas and compresses it into a high pressure, high temperature gas.

CONDENSOR

The **condenser** accepts the gas from the compressor and, through some cooling medium, condenses it to a high pressure, cool temperature liquid.

THERMAL EXPANSION VALVE

The liquid line feeds the **thermal expansion valve** or device where the liquid expands and flashes to a gas and cools.

EVAPORATOR

The **evaporator** is a heat exchanger where the expanded cold gas exchanges heat with the area being cooled. (This area may be a refrigerator, your living room, or a meat locker. The fluid generally is just normal air.)

CARNOT CYCLE

All refrigerators work on a combination of processes, cycles, which achieve cooling, and thereby liquefaction, through expansion. The Carnot cycle is a combination of isentropic and isothermal processes.

Isentropic Expansion, is where a fluid does work and expands keeping its entropy constant. This is an adiabatic process; no heat is allowed to enter or leave the system. It is also a reversible process since the work can be returned to the fluid through compression. This is the best method of expansion because it produces the largest temperature change over a given pressure. (Van Sciver 273, Sears 348)

Isenthalpic Expansion, is where a fluid undergoes a pressure change without heat transfer. This method is in common application in practical refrigeration systems for its ease of use. However, it is of lower thermodynamic efficiency because it is an irreversible process leading to non-idealities.

Sadi Carnot, (1796-1832) a French physicist and engineer, developed, in 1824, a hypothetical heat engine with a 100% efficiency. (As we learned earlier, this is contrary to the second law.) He examined this hypothetical engine and discovered that the perfect engine must avoid all irreversible processes. Every heat transfer, in his idealized cycle, must be isothermal or adiabatic.

His formula $K = T_C / T_H - T_C$, represents an ideal efficiency that can never be attained.
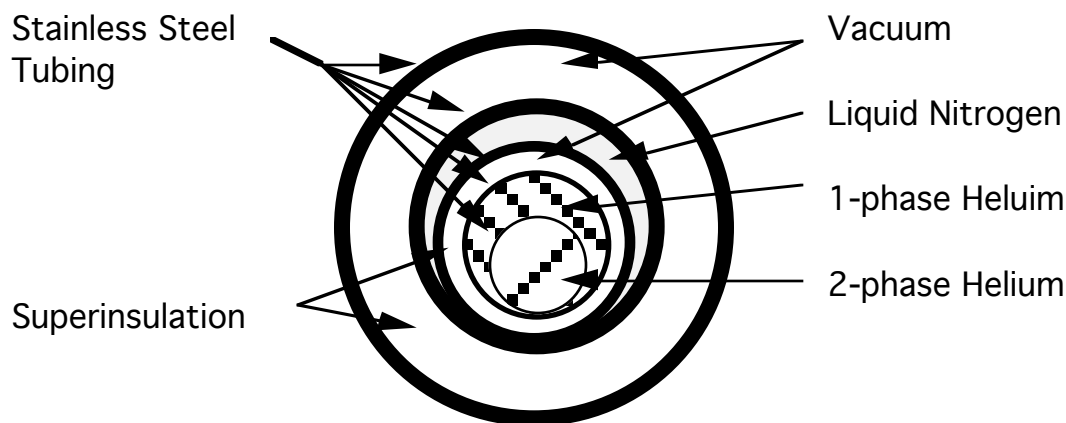
TRANSFER LINES

The efficient transfer of liquid helium, or even nitrogen, requires a vacuum-insulated line. This is because transfer lines suffer all the heat transfer problems of conduction, convection, and radiation expressed earlier. A liquid helium transfer line is vacuum jacketed and usually shielded with liquid nitrogen.
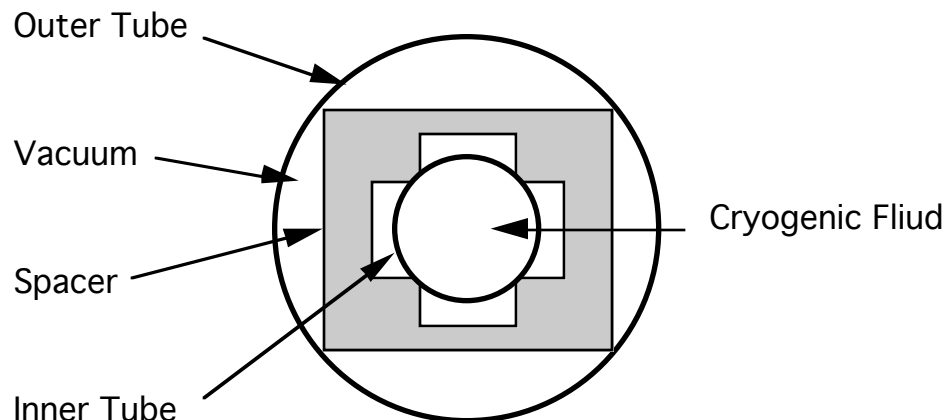
Simple Transfer Line

This simple transfer line shows how many of these problems are solved. The center tube would carry the cryogenic fluid. It is held in place by a spacer made of materials that are poor conductors of heat. The outer tube holds a vacuum to protect the inner tube.

Proton Transfer Line

This is a diagram of the Proton transfer line, but all fixed target transfer lines are constructed similarly. The transfer line consists of five stainless steel tubes that hold vacuum and superinsulation, spacers (not shown), liquid nitrogen, two-phase helium, and single-phase helium. The vacuum, insulation (wrapped at 60 layers per inch), and liquid nitrogen all act as a shield for the supply and return helium.

The innermost tube handles the two-phase return from the magnet string. The next outer tube supplies the magnet string with liquid helium . You may think it odd that we have a gas and a liquid in contact, by conduction, with each other, but please note that these two tubes do not act as a heat exchanger in the way you might think. The returning two-phase gas, flowing through the center tube, is expanded after leaving the magnet string. The affect of this expansion is that

the two-phase return gas becomes slightly colder than the single-phase supply, thus the two-phase return gas acts as a precooler for the supply line.

CRYO VALVES

Cryogenic valves are necessary to control the flow of both gas and liquid phases flowing through the refrigerator. The best valves offer the following characteristics: low heat leak, reliable operation, small heat capacity, small resistance to flow, simplicity and economy of construction, and adaptability of insertion into ordinary vacuum-insulated lines. The following information on Kautzky valves describes one of Fermilab's more important developments.

THE KAUTZKY VALVE

The development of Fermilab's cryogenic system required new components, one of which was a relief valve that could reseal itself after venting. The Kautzky valve is a pressure relief valve used on every superconducting magnet. The valve vents helium in the event that internal pressure raises too high, as from a quench, and then reseats itself.
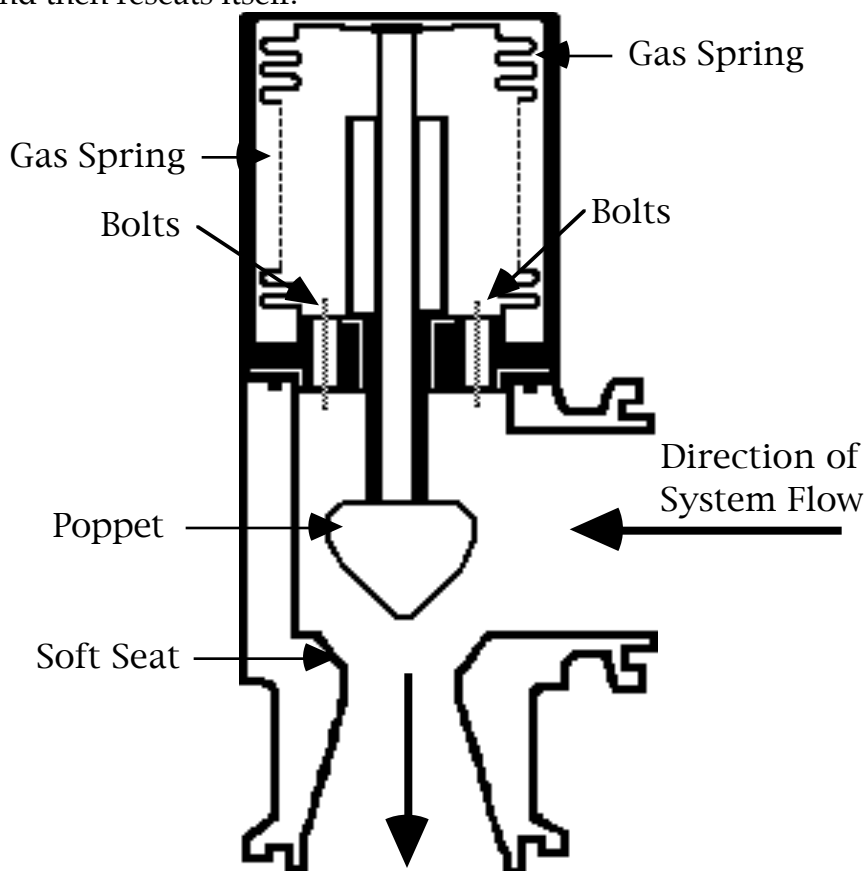

The most important aspect of the Kautzky valve is its chatter free ability to open and reseal. It's able to do this because the poppet moves counter to the flow when opening. During a quench, the seating force is reduced by the high cryostat pressure acting on the inner surface of the actuator, which opposes the "gas spring." When the force holding the poppet on its seat is reduced to zero,

the poppet begins to open. The force of this flow pushes the poppet fully open. Even as the flow past the poppet equalizes, the poppet remains open down to a few psi less than the pressure that caused it to open. If the pressure continues to drop, the remotely supplied pressure of the "gas spring" will close the valve.

HEAT EXCHANGER (HEX)

Heat transfer occurs when objects, gasses, or fluids of different temperatures come into contact with each other. The modes of heat transfer are through **conduction**, **convection**, or **radiation**.

Heat Exchanger
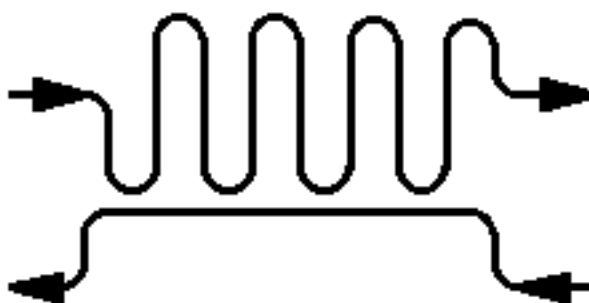
There are many types of heat exchangers used in cryogenic systems. This discussion will limit itself to the types of heat exchangers used by the Main Ring and the Research Division in their satellite refrigerators. The construction of these heat exchangers is commonly referred to as tube and shell exchangers.

TUBE & SHELL HEAT EXCHANGERS

The tube portion is a finned copper tubing, which is wound around a mandrel in a spiral configuration like a spring. The return shell path is an annular space surrounding this tube bundle. Heat exchange is accomplished by **convection** from the fluid over the surface of the copper tubing and by **conduction** through the tubing wall. The entire assembly is enclosed in a vacuum vessel and super insulated to reduce heat loss to the ambient environmental temperature.

COUNTER FLOW

T° in   T° out
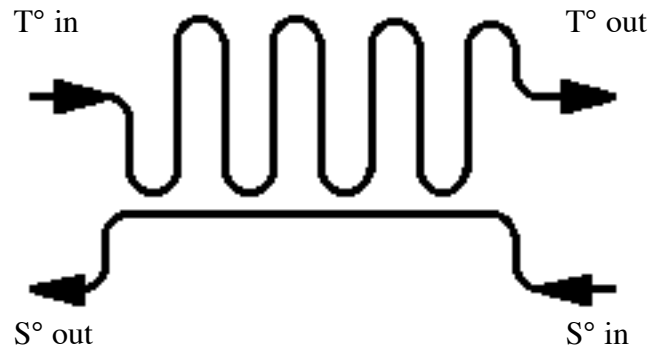
S° out   S° in

T° in = S° out   and   T° out = S° in

In a <u>perfect</u> heat exchanger, the counter flow streams exchange heat with <u>100%</u> efficiency. The supply side outlet temperature would be equal to the return side inlet temperature and the supply side inlet temperature would equal the return side outlet temperature. Unfortunately, there are no perfect heat exchangers. There are always losses due to inefficient insulation, poor vacuum and heat transfer through materials such as copper.

Even though this is not a perfect heat transfer, it is very important to understand these temperature relationships. So let's follow a cascade of heat exchangers and see the temperature ranges.

HEX I

300°K   80°K

Helium
In

Nitrogen
In

300°K   80°K
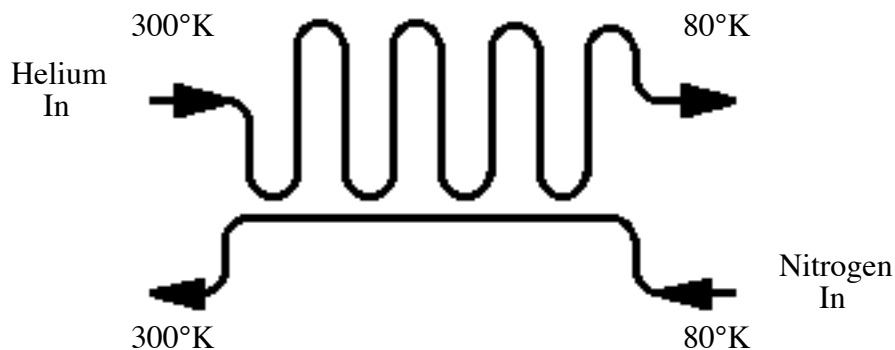
Heat exchanger I, in a satellite refrigerator system, uses liquid nitrogen on the "shell" side as the cooling medium. The "tube" side, which contains the hot helium gas, is totally immersed in a bath of liquid nitrogen. This is probably the most efficient heat exchanger in the entire refrigerator. The helium stream is cooled to nitrogen temperature as it winds its way through the tube bundle. The nitrogen enters the heat exchanger as a liquid at 80°K and leaves as a gas at about 265°K.
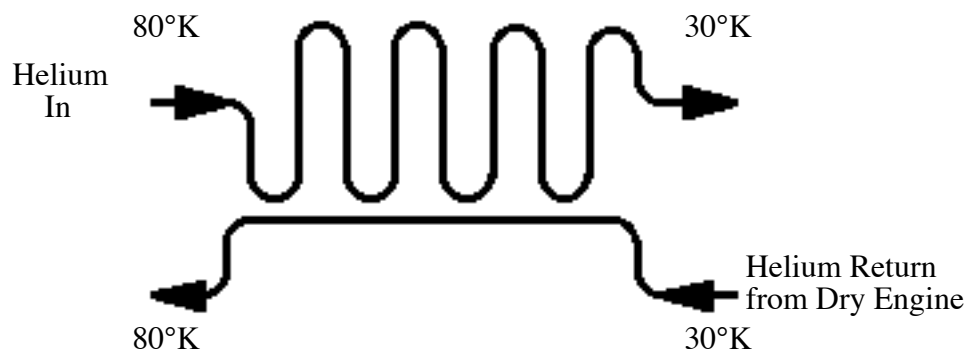
HEX II

300°K   80°K

Helium In

Helium Return from Dry Engine

300°K   80°K
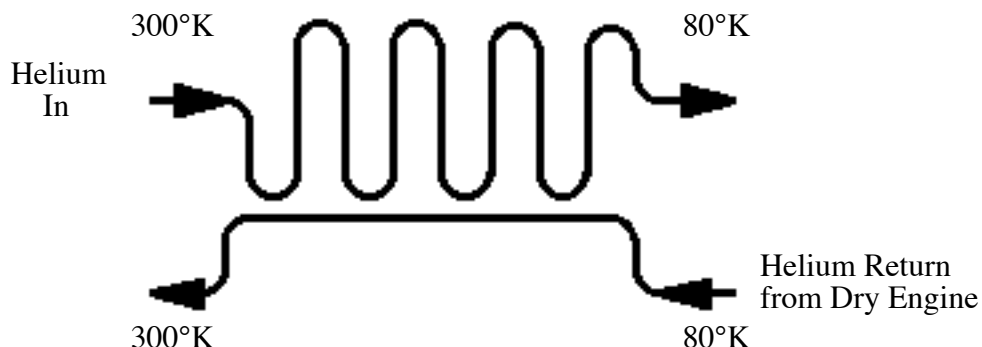
Heat exchanger II exchanges heat from the supply helium to the returning helium stream. HEX 2 is only put on line once the dry expander is running and cooling. (A system such this is called a non-star refrigerator.)

In a star refrigerator system, HEX II is actually two heat exchangers, which are labeled II and IIa here at Fermilab. HEX II works like a non-star refrigerator in that it takes the return supply of helium from the dry engine to cool the incoming gas, but it also has HEX IIa which exchanges heat with the in coming liquid nitrogen supply to HEX I. (The flow path is illustrated in the Star system diagram.)

HEX III

80°K   30°K

Helium In

Helium Return from Dry Engine

80°K   30°K

HEX III is a straightforward counter flow helium to helium heat exchanger in the bootstrap chain. (A bootstrap operation is one that operates without outside help.) Its purpose is to reduce the temperature of the supply stream prior to expansion by the dry expander. This heat exchanger's operating temperature is achieved as a result of the dry expander.

HEX IV

30°K   5°K

Helium
In

Helium Return
from Wet Engine

30°K   5°K
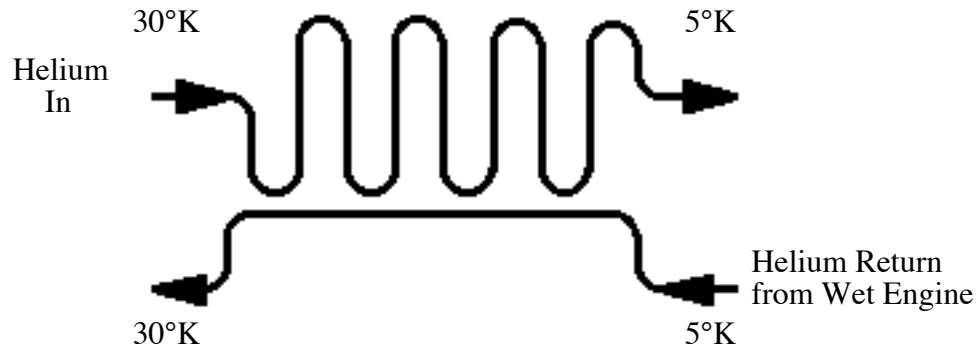
HEX IV is cooled as a combined effort of the dry expander and wet expander outlet, and from the return flow from the system.

NON STAR

Nitrogen
Out

Nitrogen
In

HEX I

Helium
In

Helium
In

HEX III   HEX IV

Helium
Return
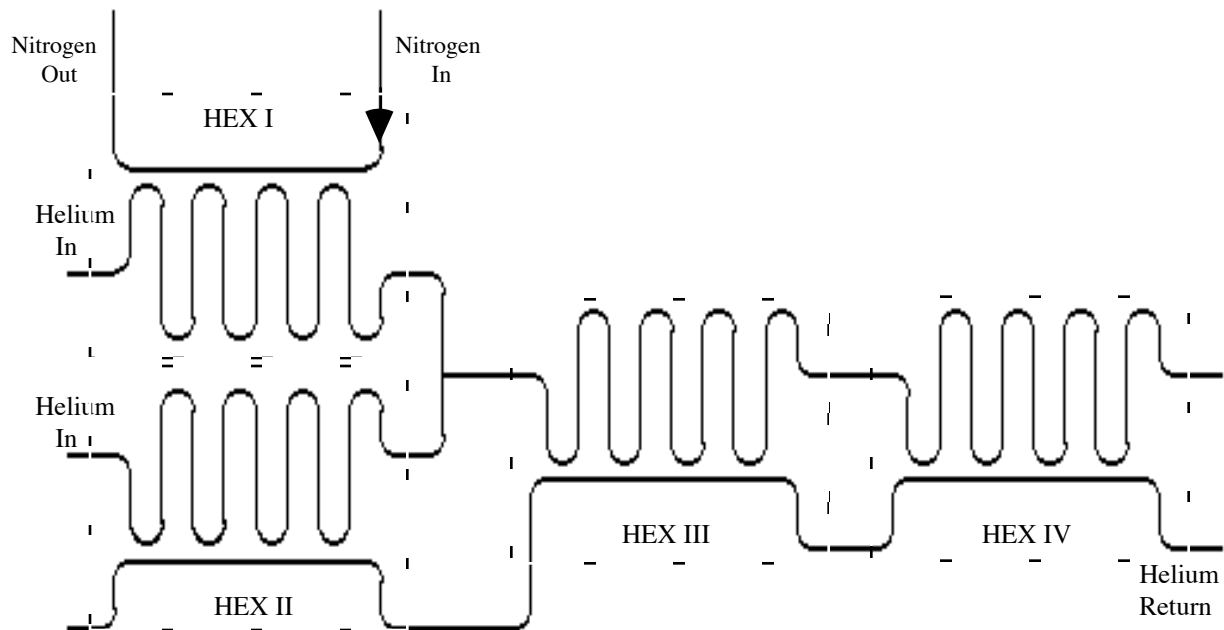
HEX II

This flow diagram shows a non-star flow path without expansion engines. This configuration is used at PS1. (Note the lack of HEX IIa.)
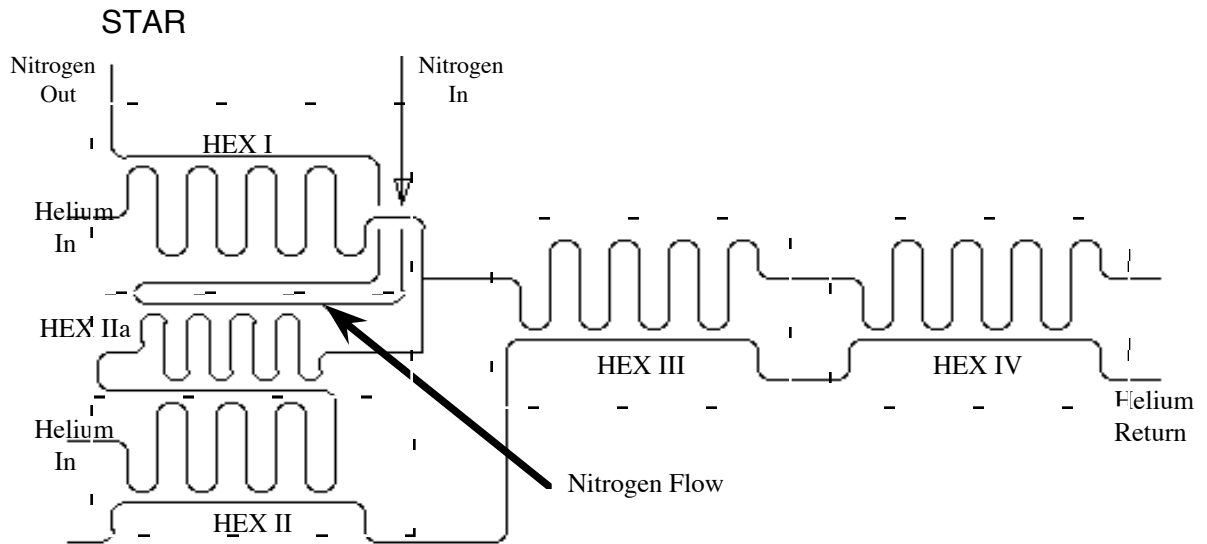
STAR

This is the flow path of a star HEX without the expansion engines. Follow the path of Liquid nitrogen and how it relates to HEX IIa. This configuration is used at Meson and PS4.

STAR WITH EXPANDERS
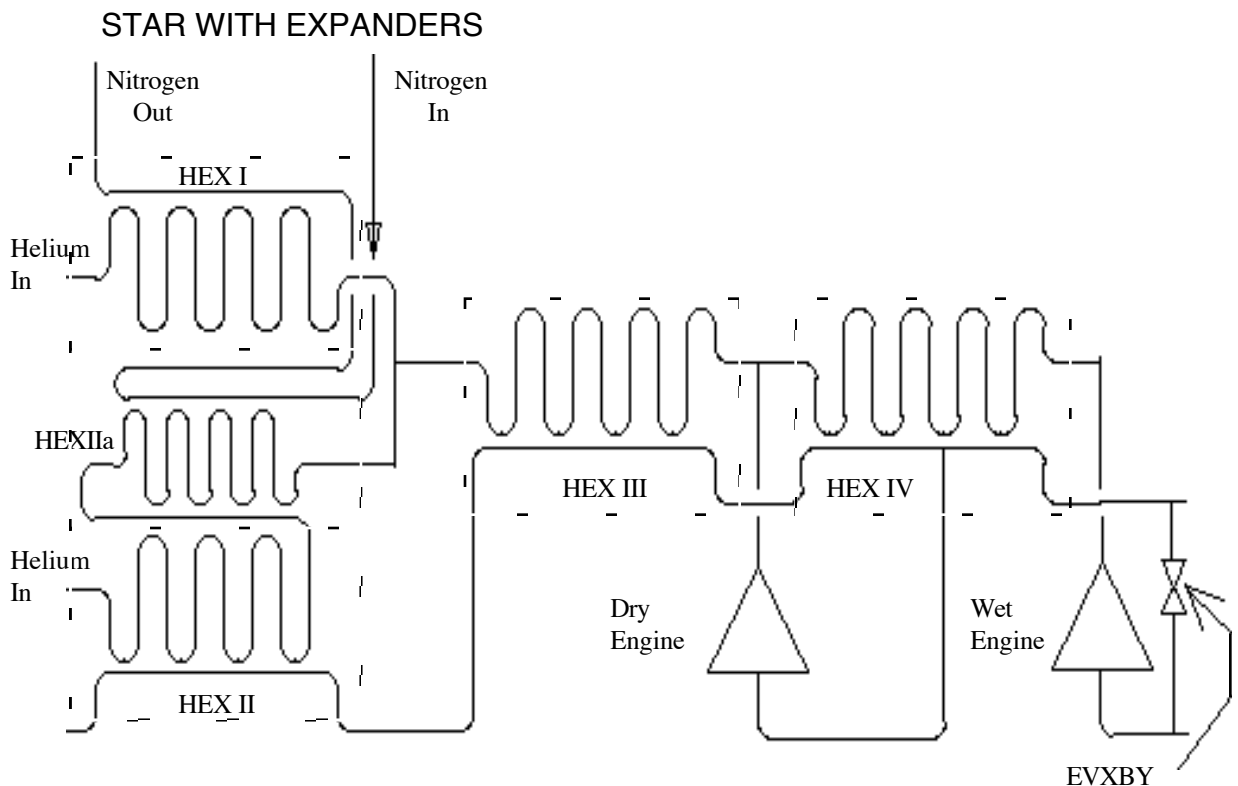
This diagram includes the expansion engines and shows, approximately, where each engine receives gas and thereby aids in cooling. Note the valve that would allow the Wet expander flow to enter the return flow path. This valve would be EVXBY.

ENGINES

According to the Random House Dictionary, engine is defined as "a machine for converting thermal energy or power to produce force and motion."
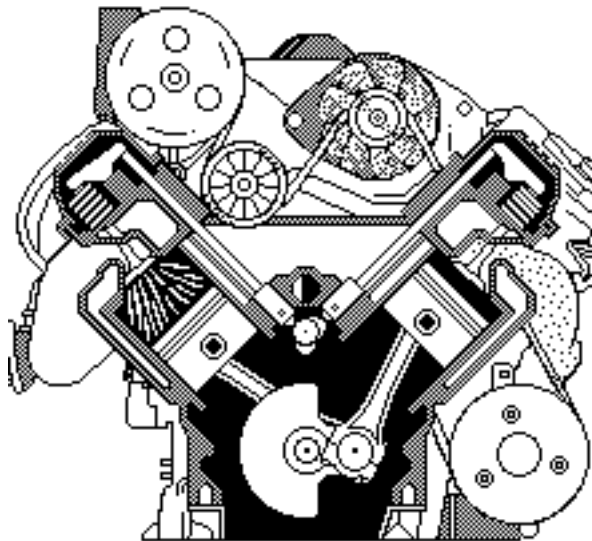
The engine pictured here is one of the most commonly found types in the world, a combustion engine, and follows the dictionary definition to the letter.

Our cryogenic systems in the External Beamlines use engines in a slightly different way — to cool and liquefy helium gas.

The French engineer Georges Claude introduced the reciprocating expansion-engine refrigerator in 1902. In principle, it was simply a reciprocating piston-and-cylinder engine similar to the steam engine that had been in use for over a century.

The thermal energy in the high-pressure helium stream, is used to create force and motion by the expansion of the gas which in turn drives the flywheel and motor generator. Unlike a combustion engine, the desired result is not the motion created but the temperature drop caused by the expenditure of energy in the form of sensible heat. To see how this happens, let's examine a cryogenic expansion cycle.


EXPANSION ENGINE CYCLE

A   The <u>inlet valve</u> opens allowing high pressure (250 to 300psig) helium gas to enter the cylinder resulting in driving the piston in an upward motion.

A   B   C   D
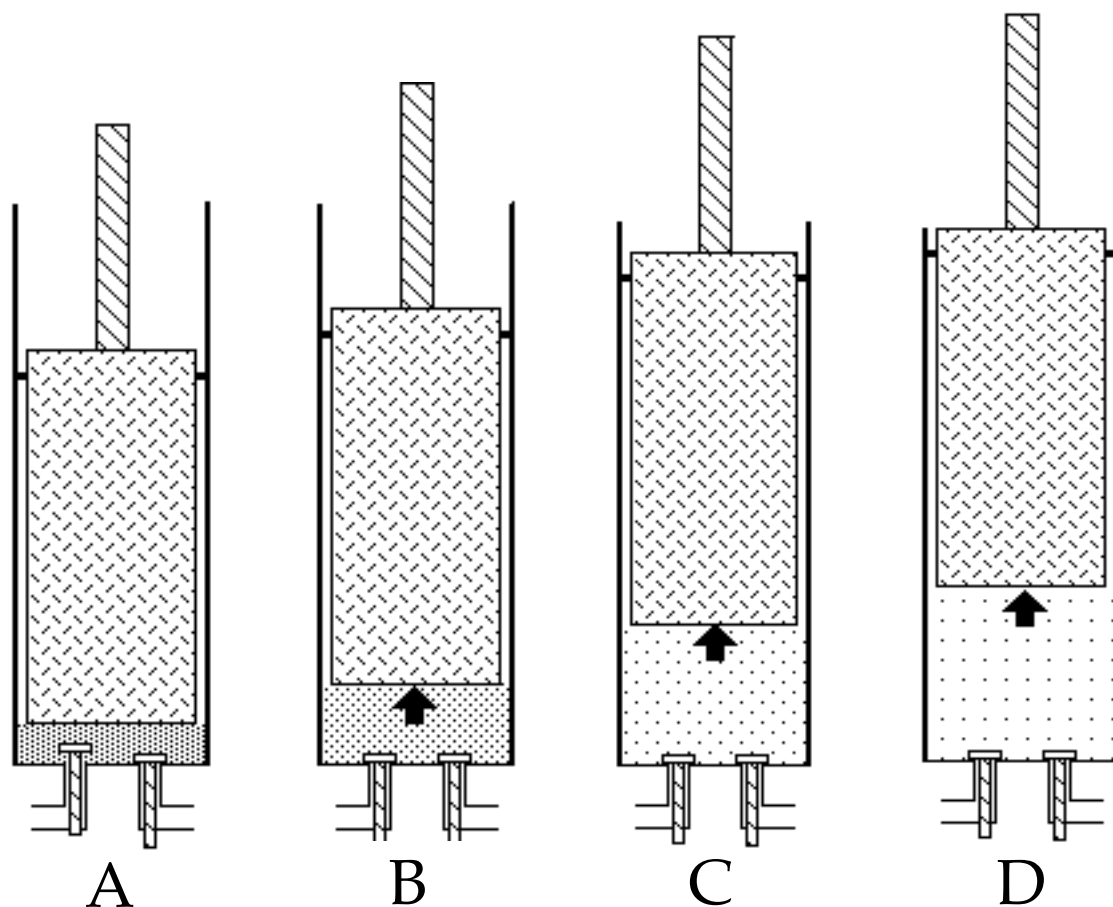
B   The intake valve closes while the piston continues to move up. The gas
      expands and cools.

C   The expansion cycle continues. The gas expands and cools.

D   The piston reaches top dead center (TDC).

E   Once the piston passes top dead center the exhaust valve opens. The
      motion of the flywheel along with the second piston keeps the cycle going.
      Now the piston pushes the low pressure cold helium gas (or liquid) out of
      the cylinder.

E   F   G   H   I
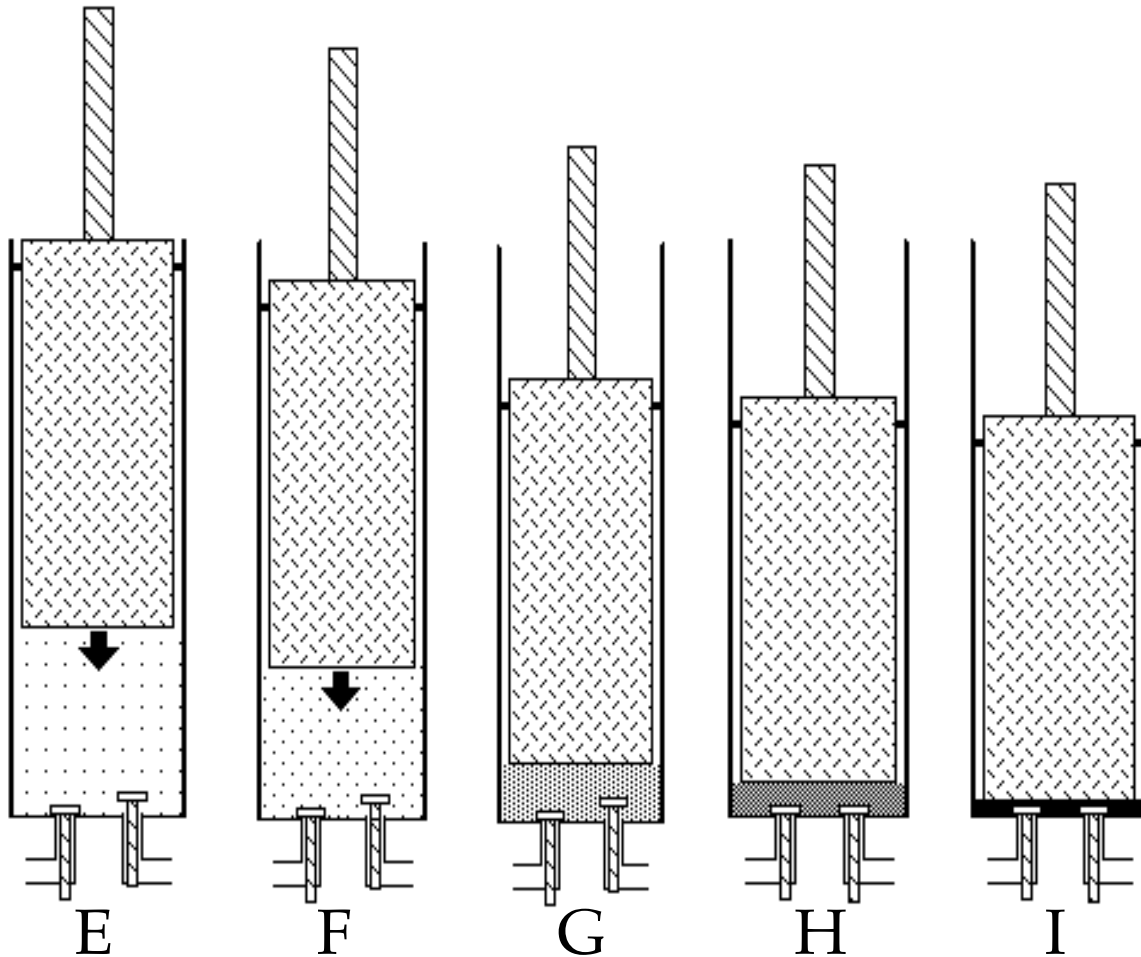
F   The piston continues downward and is being driven by the other piston and flywheel .

G   As the piston nears bottom dead center, (BDC) the exhaust valve closes.

H   The exhaust valve closes and for a short time both valves remain closed as the piston continues its downward travel . The gas in the cylinder is then compressed. This is called recompression.

I   BDC and recompression.

ENGINE TRACE

1.   Inlet valve opens and pressure goes up.
2.   Inlet closes and pressure drops off. Point 2 to 3 is the expansion cycle.
3.   Exhaust valve opens and pressure abruptly drops.
4.   Exhaust closes causing slight recompression of gas.
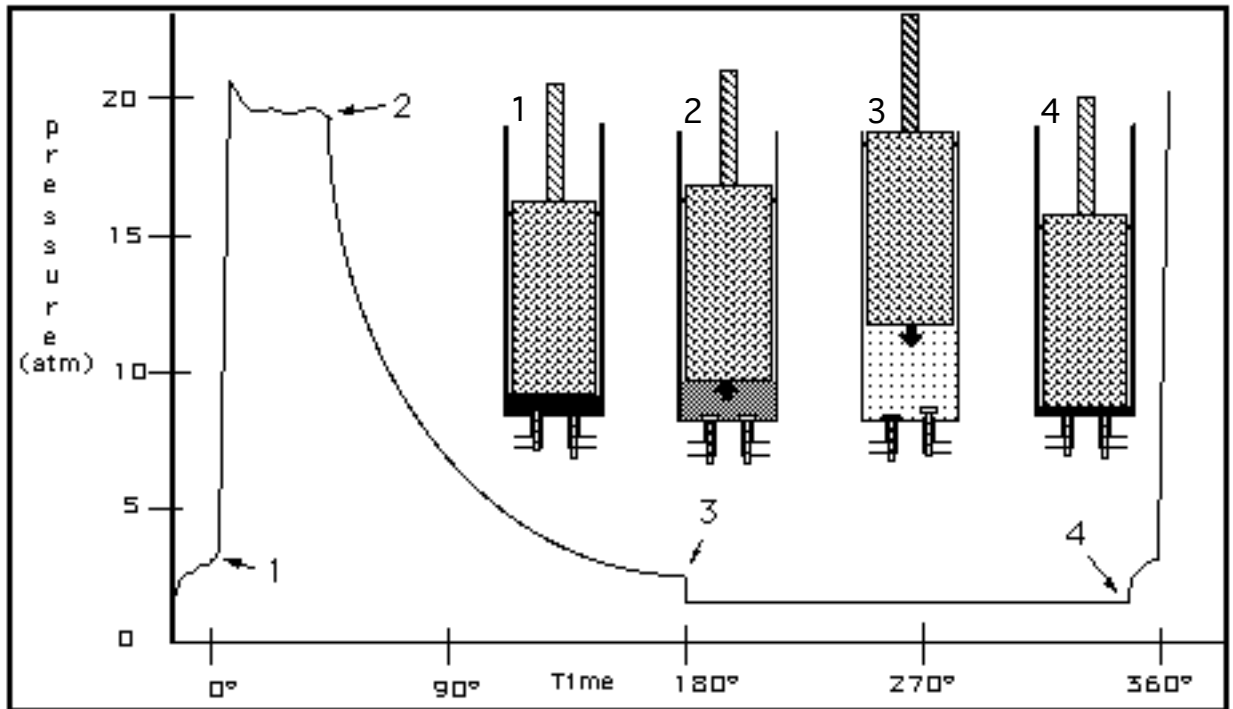
This illustration is a plot of the cylinder pressure vs. time. The degree increments indicate approximate piston position.

ENGINE EFFECIENCY PLOT
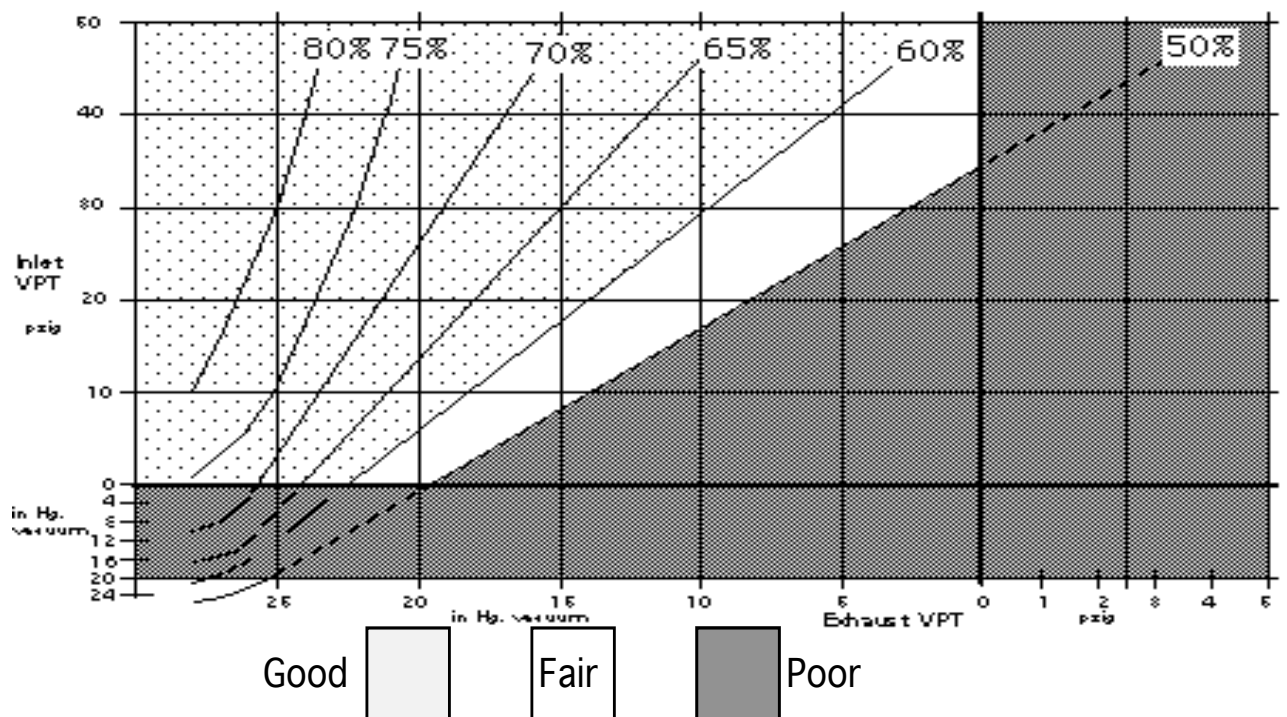
This efficiency plot functions as a ratio of the inlet pressure to the outlet pressure.

27

The inefficiencies of Fermilab's expansion engines are usually due to valve leaks caused by poor lifter clearance, or valve damage caused by dirty valves.

TEMPERATURE MEASURING DEVICES

VPT

A vapor-pressure thermometer consists of a bulb filled partly with a liquid or solid and partly with vapor in equilibrium with the condensed phase. The bulb is connected by a pressure-transmitting line to a pressure-measuring instrument. The VPT can be an extremely precise instrument; this is especially true when the lower-boiling elements are used(Scott 115), such as helium.

A VPT operates on the principle that in a closed system, which is at equilibrium, the pressure will remain constant as long as the temperature remains constant. If the temperature in the VPT's bulb drops through conduction, part of its bulb's liquid will condense and change the system's volume; thus, pressure will correspond to temperature.
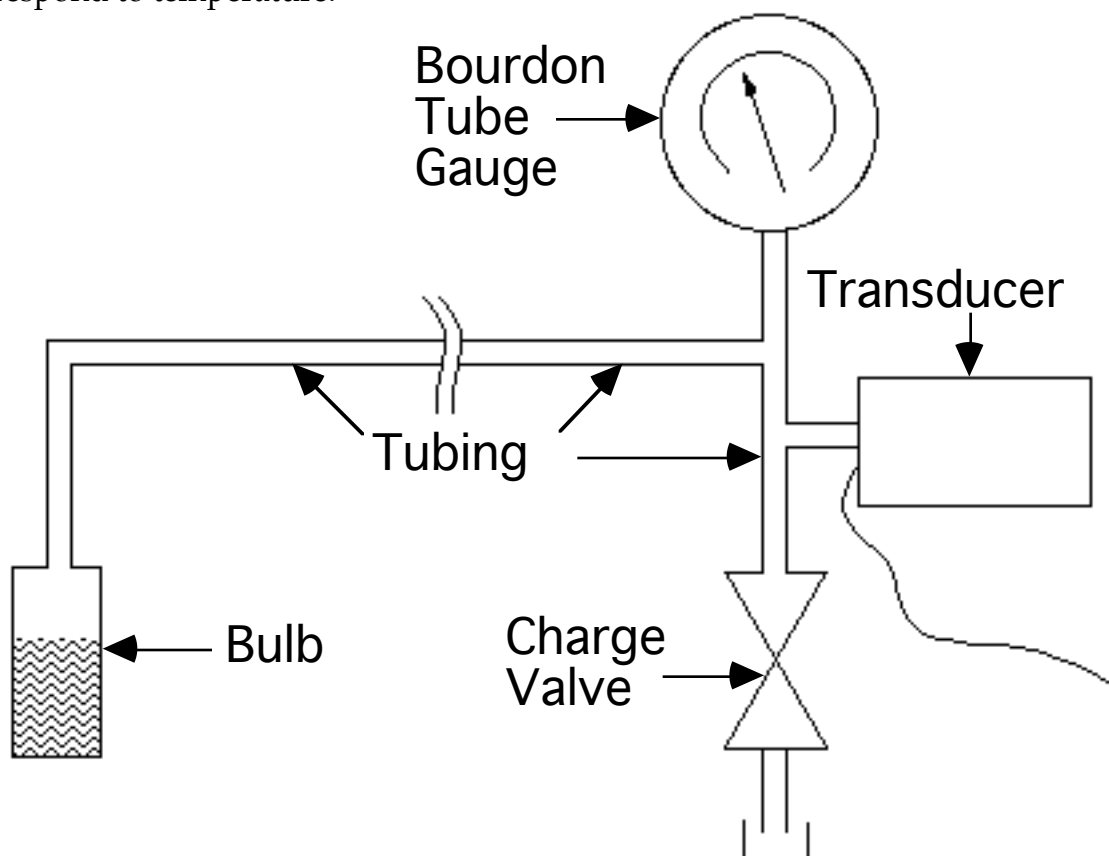
Bourdon Tube Gauge: Compound gauges are used on certain VPTs since some vapor pressures can be sub-atmospheric.

Bulb: The bulb itself is small and should contain some liquid when in the proper temperature range. The bulb should be filled partly with liquid and vapor in equilibrium with the condensed phase connected via tubing to a pressure measuring device. (It's the condensation of gas that reduces the pressure contained in the bulb and tubing, and it's this lowering of pressure that corresponds to a lowering of temperature.)

Transducer: An optional transducer is used when computer controls or read back are needed.

Charge Valve: The charge valve is used to correct the gas pressure. A typical pressure in a VPT is 100 psig at ambient temperature. This valve is capped when not in use to help eliminate leakage.

Tubing: The volume of the VPT system is crucial for proper performance. The tubing Inner Diameter (ID) needs to be small if long runs are made.

Types of Gases: Nitrogen, Argon, Neon, Hydrogen, and Helium VPTs are commonly found in the Research Division Systems. These gases are selected for their liquid temperature range.

<div align="center">

Some Temperature Ranges

Helium	2.27°K -	4.5°K
Neon	21.1°K -	27.7°K
Hydrogen	13.°K -	21.1°K
Nitrogen	62.7°K -	80°K

</div>

RESISTORS

The resistivity of a pure metal near room temperature is approximately proportional to its absolute temperature. This property of pure metal is applied in a very successful temperature-measuring instrument, the *resistance thermometer*(Scott 128).

CARBON RESISTORS

Carbon resistors are used to read low temperatures because they're sensitive at lower temperatures such as 80°K and lower.

Ω vs°K Carbon
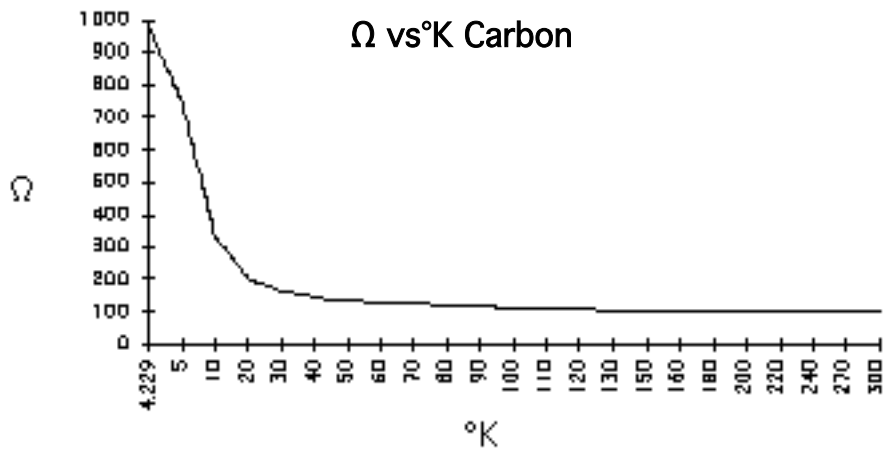
As the plot indicates, the relationship between ohms and temperature with carbon resistors is not linear.

PLATINUM

Platinum resistors are used to read low temperatures because they're sensitive at temperatures down to approximately 30°K. In lower temperature ranges the sensitivity of platinum resistors suffer.

Ω vs °K
Platinum
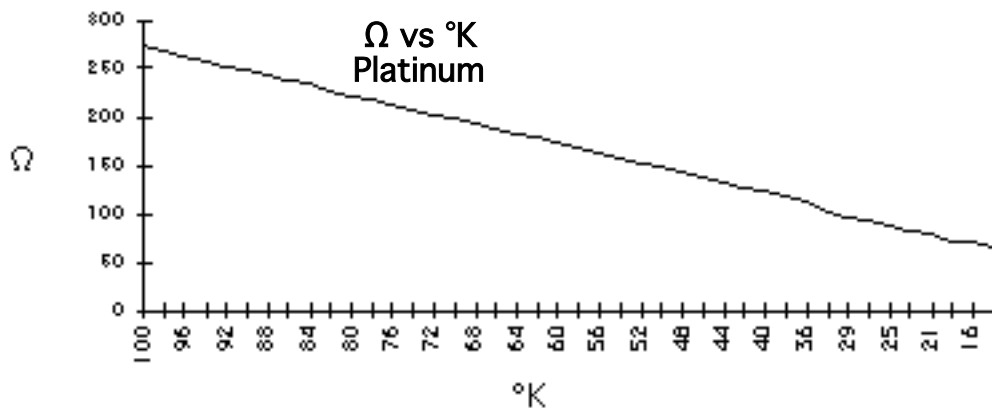
The plot indicates that the relationship between ohms and temperature is linear with platinum resistors. They are used where liquid nitrogen or argon temperatures are expected, up to or above ambient.

VACUUM

The Italian physicist Torricelli (1608-1647), inventor of the barometer, is credited with beginning the study of vacuum techniques by his experiments on the

existence of a pressure due to air. Pascal (1623-1662) continued this research by showing the reduction of air pressure at different altitudes. Boyle (1602-1686) invented the first mechanical vacuum pump.

The classical definition of a vacuum is an enclosed space devoid of any gases or vapors. This definition, of course, is impossible to achieve. The best that can be accomplished is an area of low pressure where most of the gases and vapors have been removed.

James Dewar (1848-1923) was the first to use vacuum insulation. His invention, the double-walled glass vessel with a high vacuum in the space between the walls, is now a common article in research laboratories. Any vessel that utilizes vacuum insulation to prevent heat flow is called a dewar.

Dewar designed his vessel after studying the 1820s research of Dulong and Petit who discovered the following two properties of insulation:

1. There is no convective transfer of heat between walls confining gas at sufficiently low pressure.
2. The emission or absorption of thermal radiation by the surface of a material grows weaker as the reflectivity increases. (Scurlock 155)

Vacuum insulation can almost completely eliminate two of the principal modes of heat transfer, that of **conduction** and **convection**. When appropriate measures are taken also to minimize heat transfer by **radiation**, and conduction by solid structural members, then vacuum insulation is by far the most effective known(Scott 143).

A high-vacuum system usually consists of several items working together:

1. A mechanical pump called the fore pump, which exhausts to the atmosphere and maintains an inlet pressure in the range of 1 to about 100 microns of mercury.
2. A pipe connecting this pump to the outlet of a diffusion pump capable of reducing the pressure several orders of magnitude more.
3. A pipe of a larger diameter connecting the diffusion pump to the volume being evacuated.
4. Sometimes a second pump, called a booster pump, is used between the high-vacuum diffusion pump and the mechanical pump.
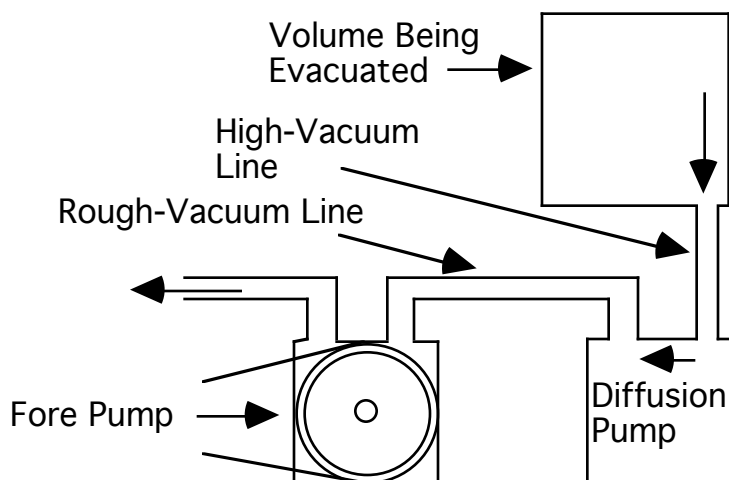5. It is also customary to provide a cold trap to remove condensable vapors(Scott 155).

Diagram of a Simple Vacuum System

Some of the different types of vacuum pumps are diffusion pumps, ion pumps, cryogenic pumps, and turbo-molecular drag pumps.

CRYOPUMPING

Gas will condense on a cryogenically cooled surface. If this surface is in an evacuated enclosure, such as a vacuum shield for liquid helium, it will produce a better vacuum. This phenomenon involves not only phase change from gas to solid at the cold surface but also adsorption of the gas molecules. (Adsorb: to collect a gas, liquid, or dissolved substance, in condensed form on a surface.) The attractive feature of cryopumping is the extremely large pumping speeds that can be attained. The effect of this "pump" is that it occurs where ever there's liquid helium (or gas if the temperature is below 20°K) across a surface in conjunction with a vacuum line (all transfer lines). The surface of the pipe becomes the pump's collection point.

VACUUM VALVES

Of the many valves designed for high-vacuum use, the most reliable are those which do not depend on packing to separate the vacuum region from the atmosphere. Some valves use metal bellows and others have an elastic diaphragm of synthetic rubber pressed onto a seat by a metal member which is on the atmospheric side of the diaphragm. These are not very suitable due to air diffusion through the diaphragm.

HIGH-VACUUM VALVES

The Richards seal-off valve, developed by NBS Cryogenic Engineering Laboratory, has proved very useful. After pumping is completed the valve is closed and then the valve handle and bonnet can be removed, leaving only the closed valve seat on the evacuated apparatus(Scott 181).

VACUUM GAUGES

Since pressures measured by vacuum gauges are several orders of magnitude smaller than atmospheric pressure, most of the ordinary pressure gauges cannot be easily used in vacuum work. In fact, most vacuum gauges are secondary gauges — the pressure is not measured directly, but is inferred from measurement of other properties.

So, if pressure can't be measured directly, how is it measured?

In the free molecular flow range of low pressure, the thermal conductivity of a gas decreases as the pressure of the gas is reduced. So if a heated surface is placed within the area of this pressure range, the thermal conductivity of the gas at the prevailing pressure will determine the rate which heat is dissipated form this surface. Vacuum gauges operating on this principle use a fine wire as the heated surface. If the wire is kept at a constant wattage, the temperature of the wire can be used to indicate the pressure.

The reliability of any hot-wire vacuum gauge will suffer if the wire surface becomes too contaminated.

MKS CAPACITANCE MONOMETER

This gauge measures the true partial pressure regardless of the thermal conductivity of the gas.

THE PIRANI GAUGE

The Pirani gauge operates on the principle that the thermal conductivity of a low-pressure gas depends upon pressure, and that the resistances of most metallic conductors increase whenever the temperature of the conductor is raised. By using a metal with a high coefficient of resistance and a Wheatstone bridge for balance, pressure can be determined by measuring linear resistance. The usable pressure range for this gauge is from 1 mm Hg down to 1×10^{-3} mm Hg.

THE THERMOCOUPLE GAUGE

The thermocouple gauge also responds to changes in thermal conductivity by measuring the temperature of a heated wire. A small thermocouple mounted on

the wire generates a nonlinear voltage that can be read by a galvanometer graduated into units of pressure. The pressure range for this gauge is from 1 mm Hg down to 1 x 10^{-3} mm Hg.

This gauge, though not as accurate as the Pirani, is more physically resilient. The thermocouple gauge can be read continuously, and further, it's not affected by operation at atmospheric pressure for short periods. It measures total pressure (pressure due to vapor as well as pressure due to permanent gas). The gauge can be read remotely and it can be used to provide a control signal for other circuits. The disadvantage of this gauge is that it must be calibrated for each different gas.

THE IONIZATION GAUGE

The ionization gauge is probably the most widely used high-pressure vacuum gauge. It operates by supplying a constant current flow to an anode that ionizes any residual gas molecules. These ions are drawn to the ion collector, producing a current measured with a microammeter. Since the supply current is fixed, the ion current is proportional to the molecular concentration(Scott 179). The pressure range for this gauge is from 1 mm Hg down to 1 x 10^{-6} mm Hg.

# FLOW DIAGRAM FOR A SATELLITE REFRIGERATOR

This is a simplified flow schematic for a satellite refrigerator. It builds on the basic system you saw back in the chapter on Refrigeration.
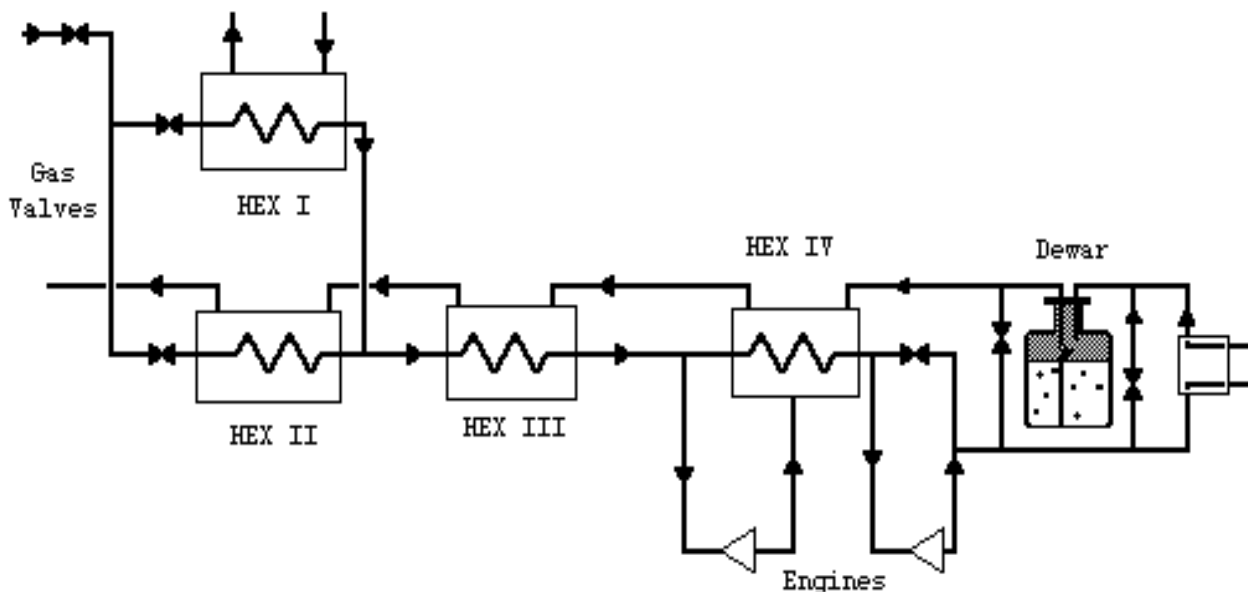
The following diagrams and descriptions explain specific parts of a satellite refrigerator system.

THE HEAT EXCHANGER VALVES

These three valves EVXHP, EVX1, and EVX2 controls the helium coming from the compressor and going to the heat exchangers.
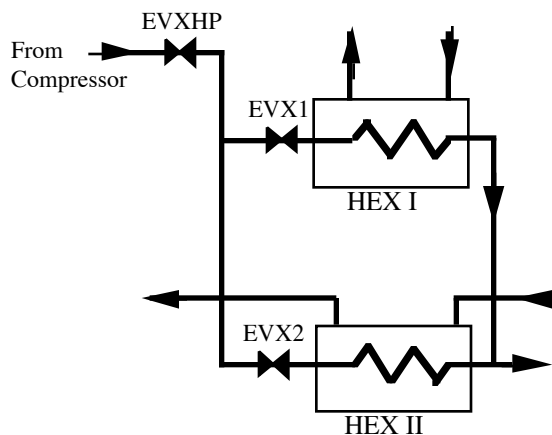
EVXHP: This valve can be found on the PS1, PS4, and MCC refrigerators. It is the main shut off of helium flow to the system. Typically, it is a ball valve that is electrically operated from the local cryo control room. When operating, this valve is used as an emergency shut off to secure high-pressure (300 psi) helium in the event of a rupture. The valve is also used to give double valve protection for some maintenance procedures.

EVX1: This valve controls the flow of helium gas through the tube side of HEX 1. This is a "Valtek" globe valve with an "Industrial Device" electric actuator. This actuator is modulated by the controls system using a PID Loop. It varies based on the helium temperature leaving HEX I. This heat exchanger is also called the nitrogen pre-cooler, which is the starting point in your Cool Down Procedure.

EVX2: This valve is similar to EVX1, but the difference involves its capability of handling much more flow. EVX2 can be opened during the cool down procedure, but only after the dry engine is running and the temperature on the shell side of HEX II is below 90°K. During normal operation this valve varies between 75% and 100% open.

THE HEAT EXCHANGER - HEX I
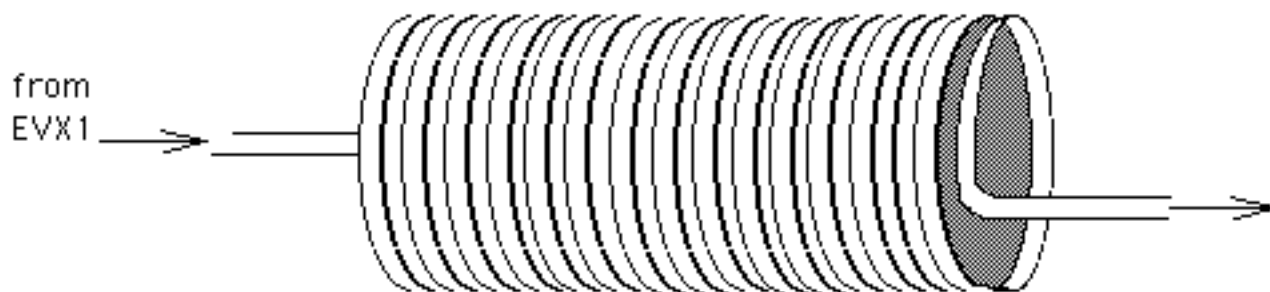
The tube side of the heat exchanger is spiral wound copper tubing and may be more than one layer deep. In HEX I the tube side is submerged in a liquid nitrogen bath. This is very likely the most efficient style of heat exchanger.

EVXLN and the LN2 POT
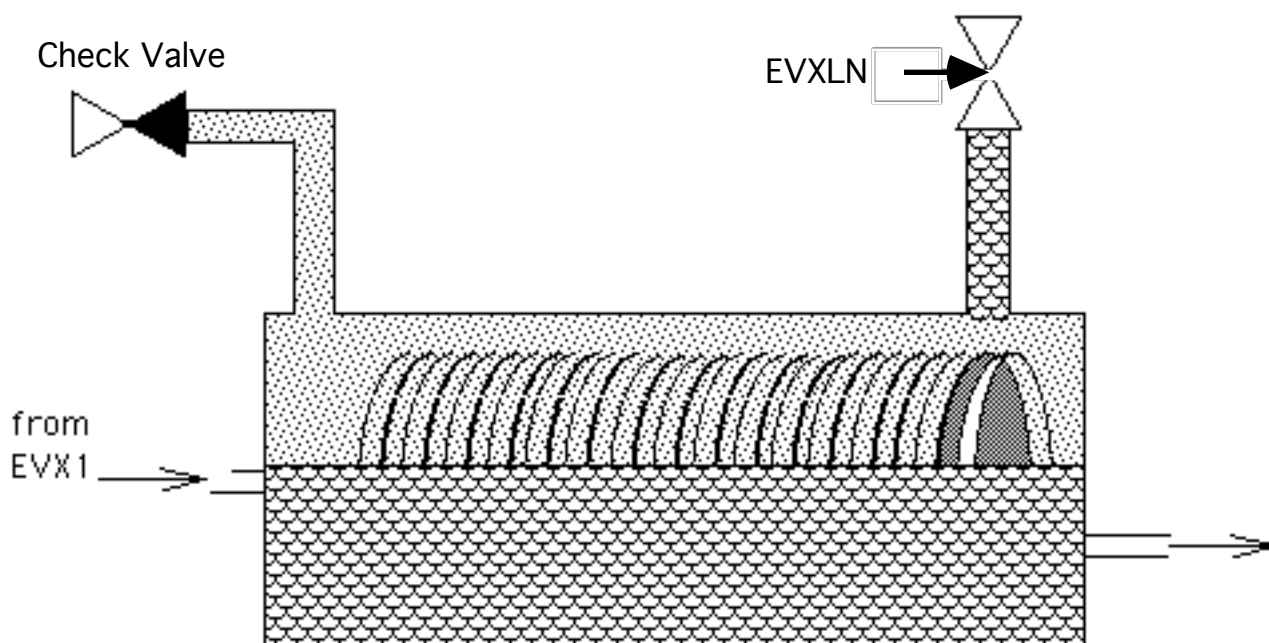
EVXLN: This valve controls the amount of liquid nitrogen flow to HEX I based on the level in the "POT." The LN_2 pot is simply a six-inch pipe mounted horizontally so it can serve as a liquid vessel for the tub side to be emersed in. The other valve is a simple check valve that vents to atmosphere.

REALITY
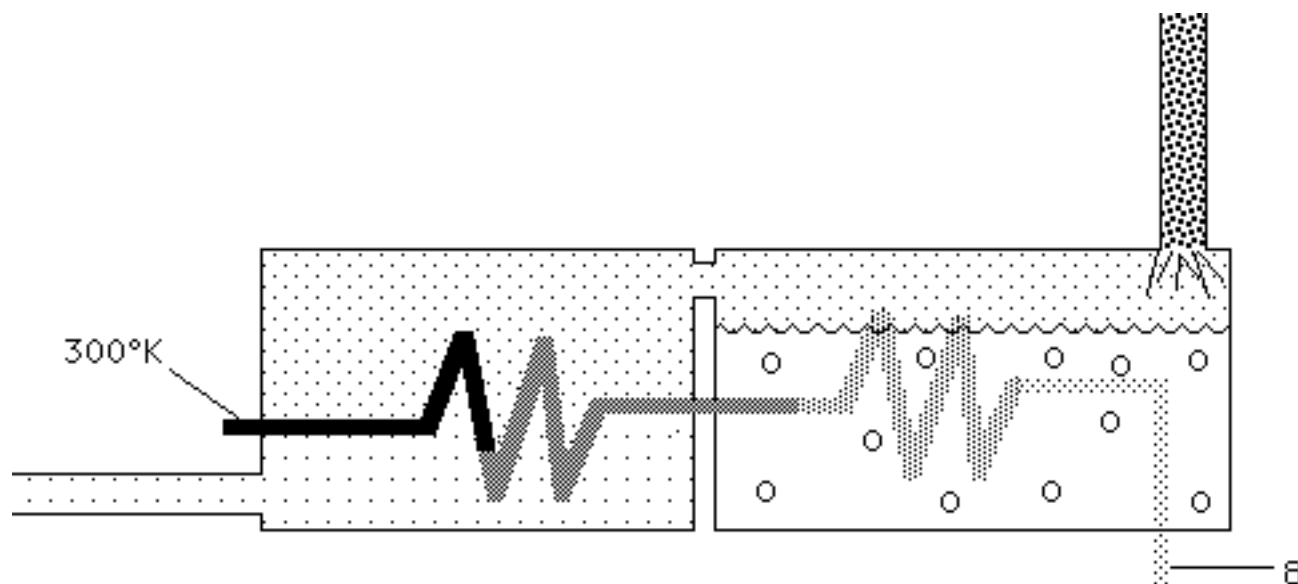
In reality, the liquid nitrogen enters and fills the pot, which covers only the last half of the tube bundle. The cold gas leaving the pot cools the first half of the tube bundle before it exits to atmosphere. This is the way the helium stream initially reaches the 80°K temperature range during cool down.

INSTRUMENTATION for HEX I
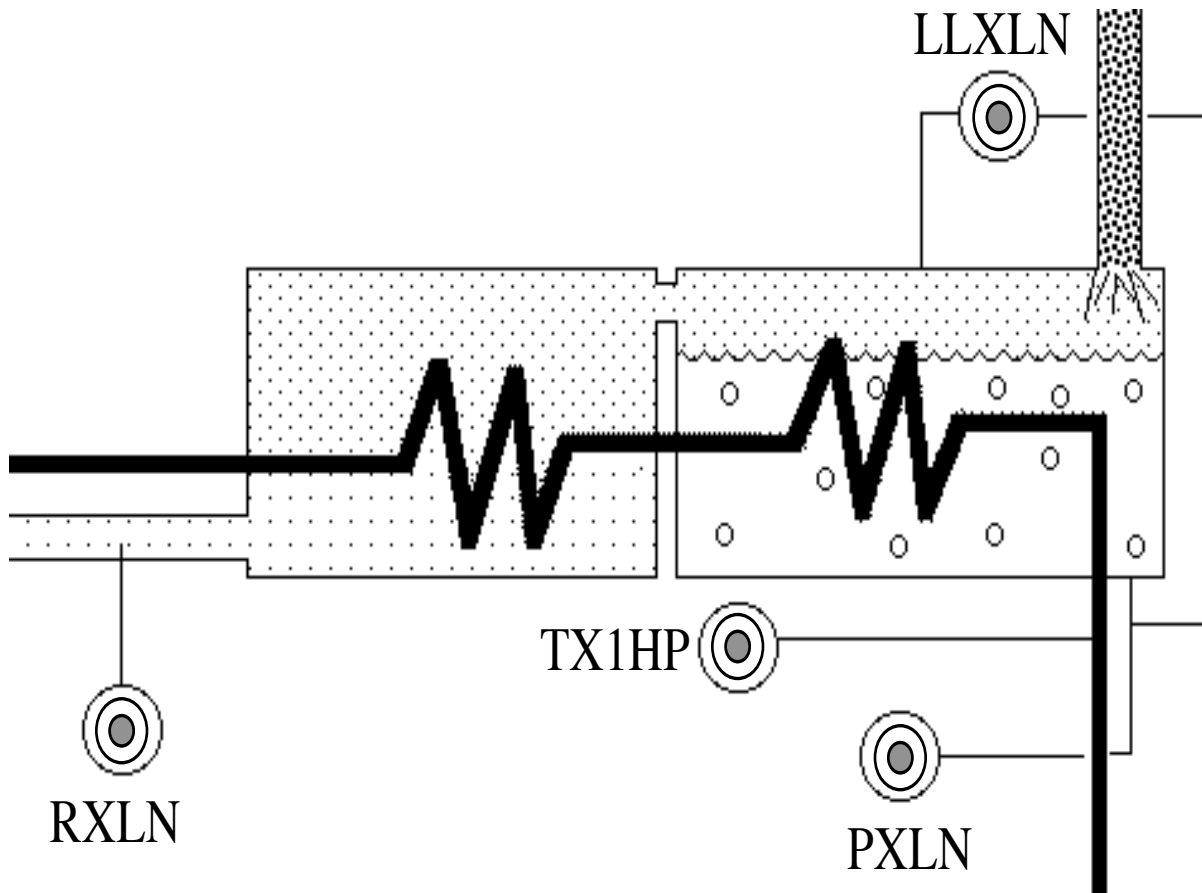
LLXN: This is a Barton ΔP transducer, which is calibrated to read the level of liquid nitrogen in the pot. Typically, this level should be 50% or greater.

RXLN: This is a carbon resistor that reads the temperature of the nitrogen leaving HEX I. Typically, this temperature should be around 265°K.

TX1HP: This is a VPT, calibrated with N_2, which reads the temperature of the helium stream leaving HEX I. Typically, this temperature is 80°K.

PXLN: This is a "Setra" pressure transducer. It reads the pressure in the nitrogen side of HEX I. This pressure is around one psig.

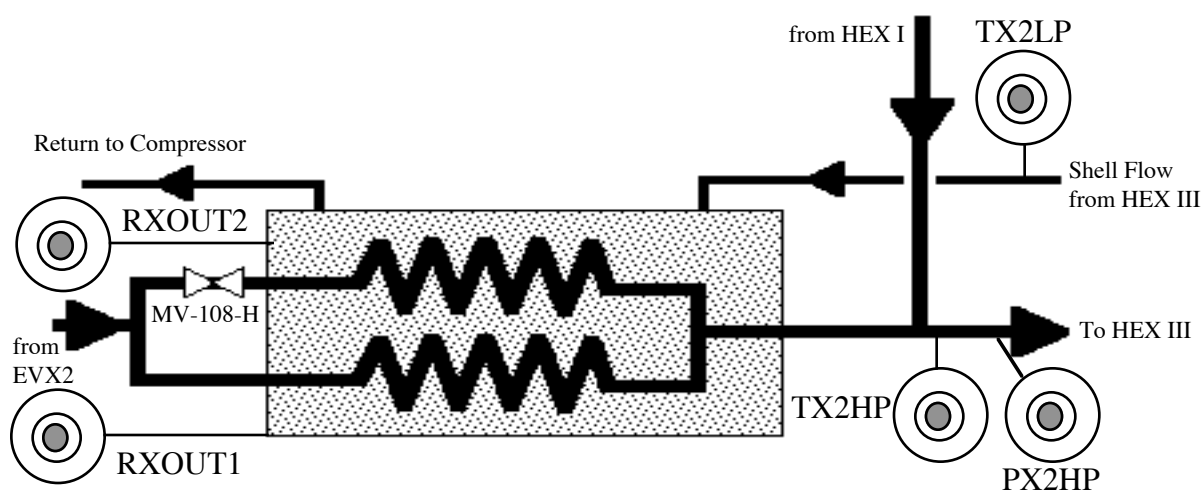**THE HEAT EXCHANGER - HEX II**

Heat exchanger two is a tube and shell type. The return flow on the shell side consists of cold gas that cools the entering high-pressure helium in the tubes.

from HEX I

Return to Compressor

Shell Flow
from HEX III

To HEX III

from
EVX2
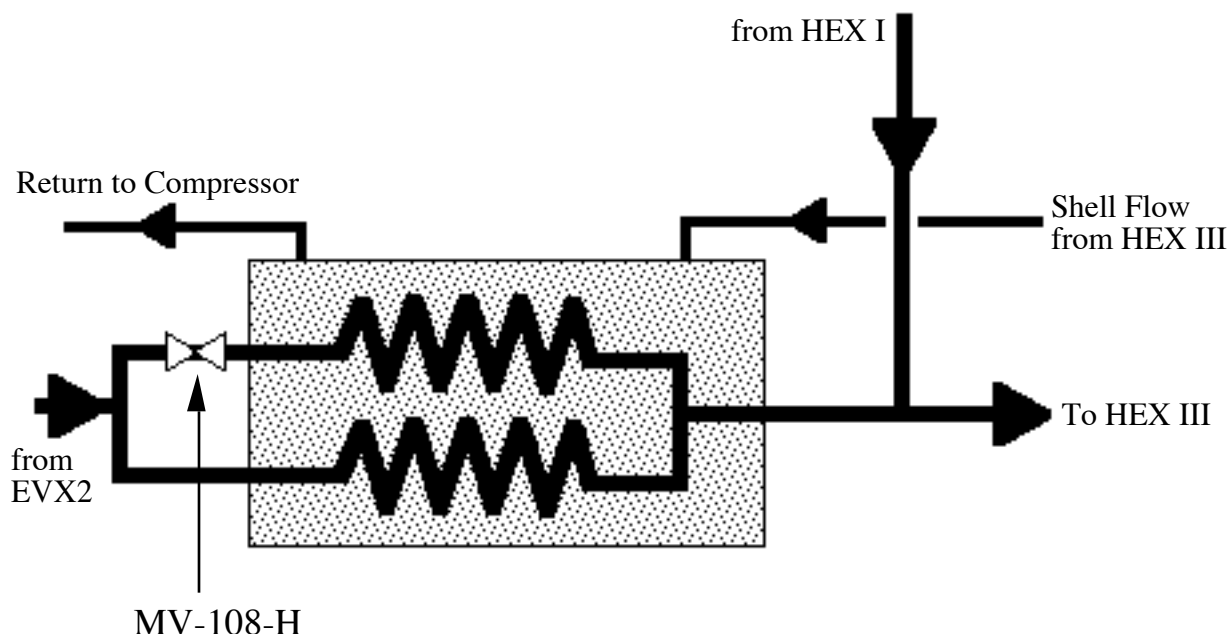
MV-108-H

MV-108-H: This manual valve is used to adjust flow through the two halves of HEX II. Proper adjustment is achieved when the outlet resistors (RXOUT 1 & 2) of the shell side are equal.

Helium Flow: As you can see, the flow path through this heat exchanger is fairly straight forward. Remember - HEX II is used only after the dry engine is running and producing sufficiently cold gas to act as a coolant for the entering high-pressure helium stream.

INSTRUMENTATION for HEX II

from HEX I   TX2LP

Return to Compressor

Shell Flow
from HEX III

RXOUT2

MV-108-H

from
EVX2

To HEX III

TX2HP

RXOUT1

PX2HP

RXOUT1: This is a shell side resistor, which reads the shell side helium as it exits HEX II. Usually, this resistor reads >280°K. (Compare this reading with that of RXout2.)

RXOUT2: This is a shell side resistor, which reads the shell side helium as it exits HEX II. Usually, this resistor reads >280°K. (Compare this reading with that of RXout1.)

TX2LP:This is a VPT charged with nitrogen gas. It reads the temperature of the shell side flow between HEX II and HEX III. Typically, this reads around 80°K.
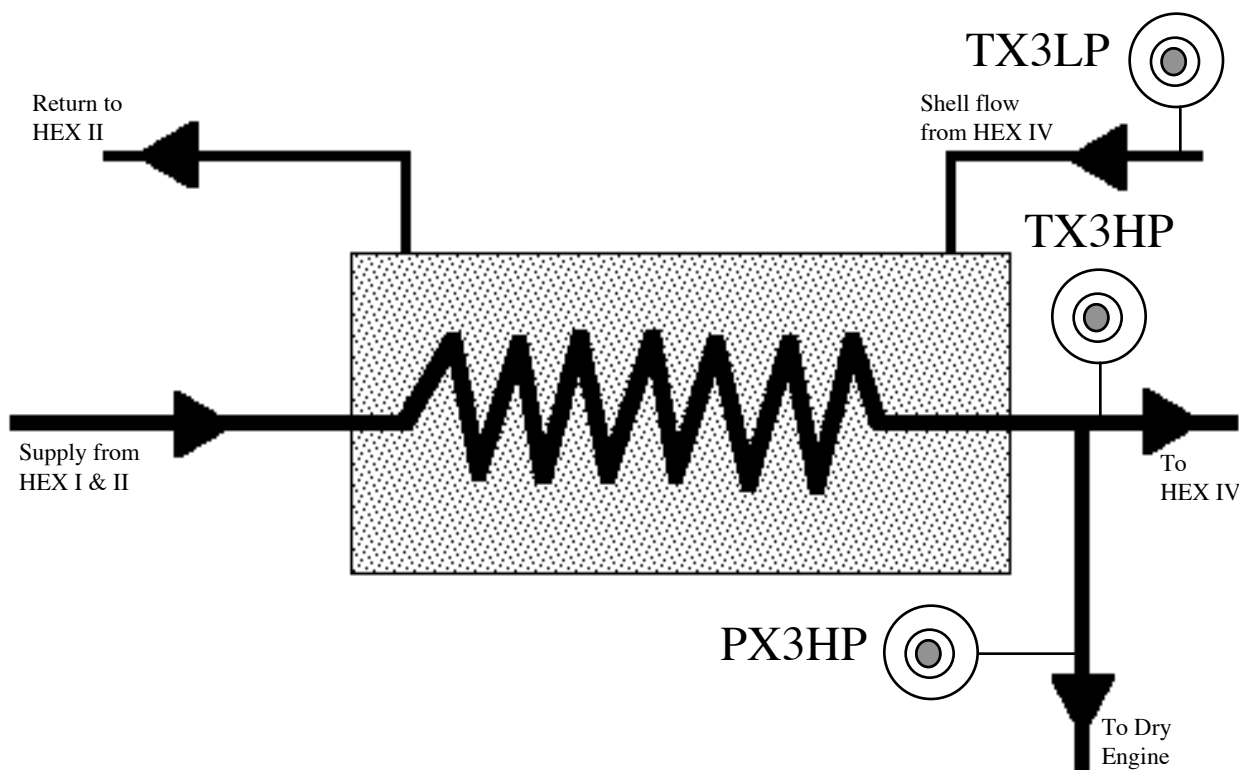
TX2HP: This is a VPT charged with nitrogen gas. It reads the temperature of the tube side flow between HEX II and HEX III. Typically, this reads around 80°K.

PX2HP: This is a 0-500 psig "Setra" transducer. It reads the pressure in the high-pressure helium supply stream as it exits HEX I and HEX II.

THE HEAT EXCHANGER, HEX III

Return to HEX II

Shell flow from HEX IV

Supply from HEX I & II

To HEX IV
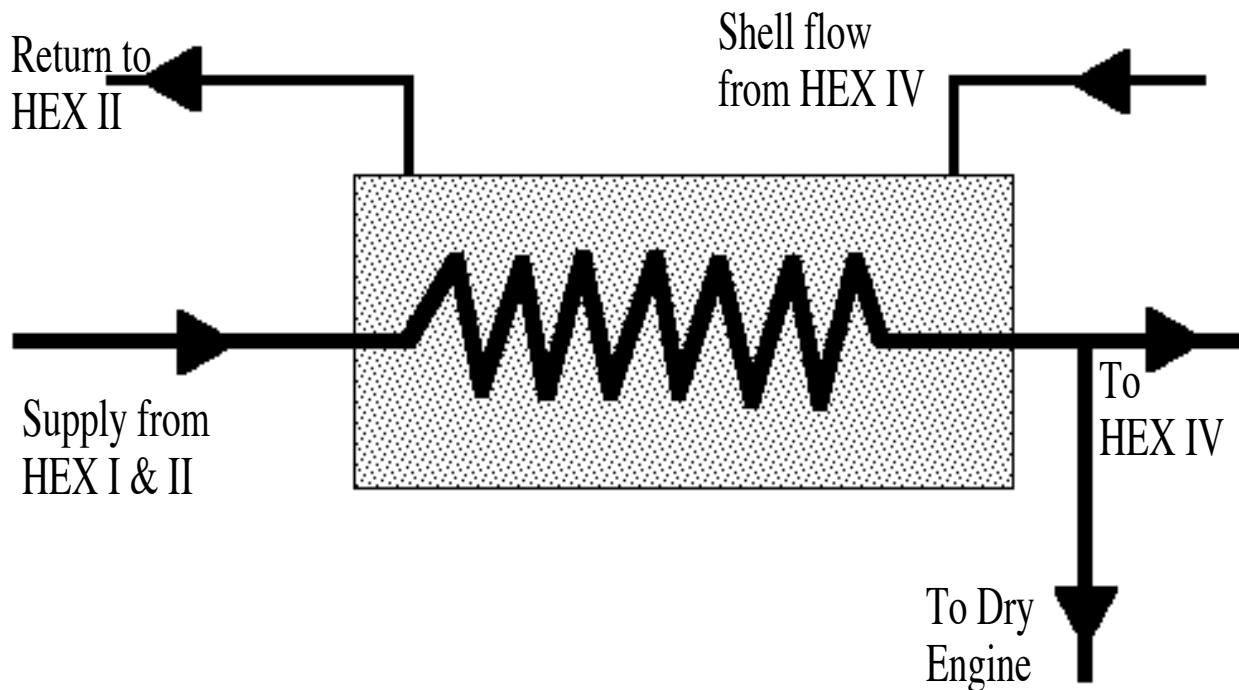
To Dry Engine

This heat exchanger is also of the tube and shell counter flow design. It continues the refrigeration process by cooling the high-pressure helium stream with cold gas returning from the dry engine through the shell side of the heat exchanger. It's also possible that two phase from the rest of the refrigerator may be in this mixture.
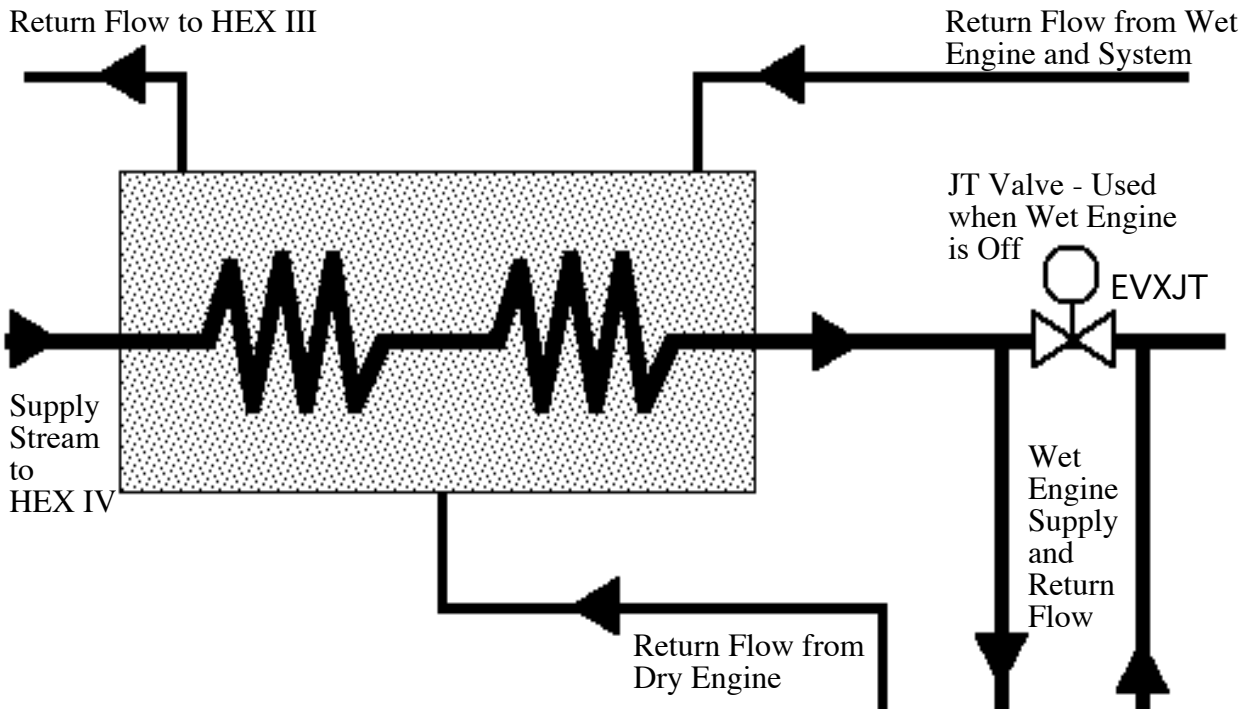
INSTRUMENTATION for HEX III

TX3LP: This is a VPT charged with neon gas. It reads the temperature of the return flow from HEX IV before it enters HEX III.
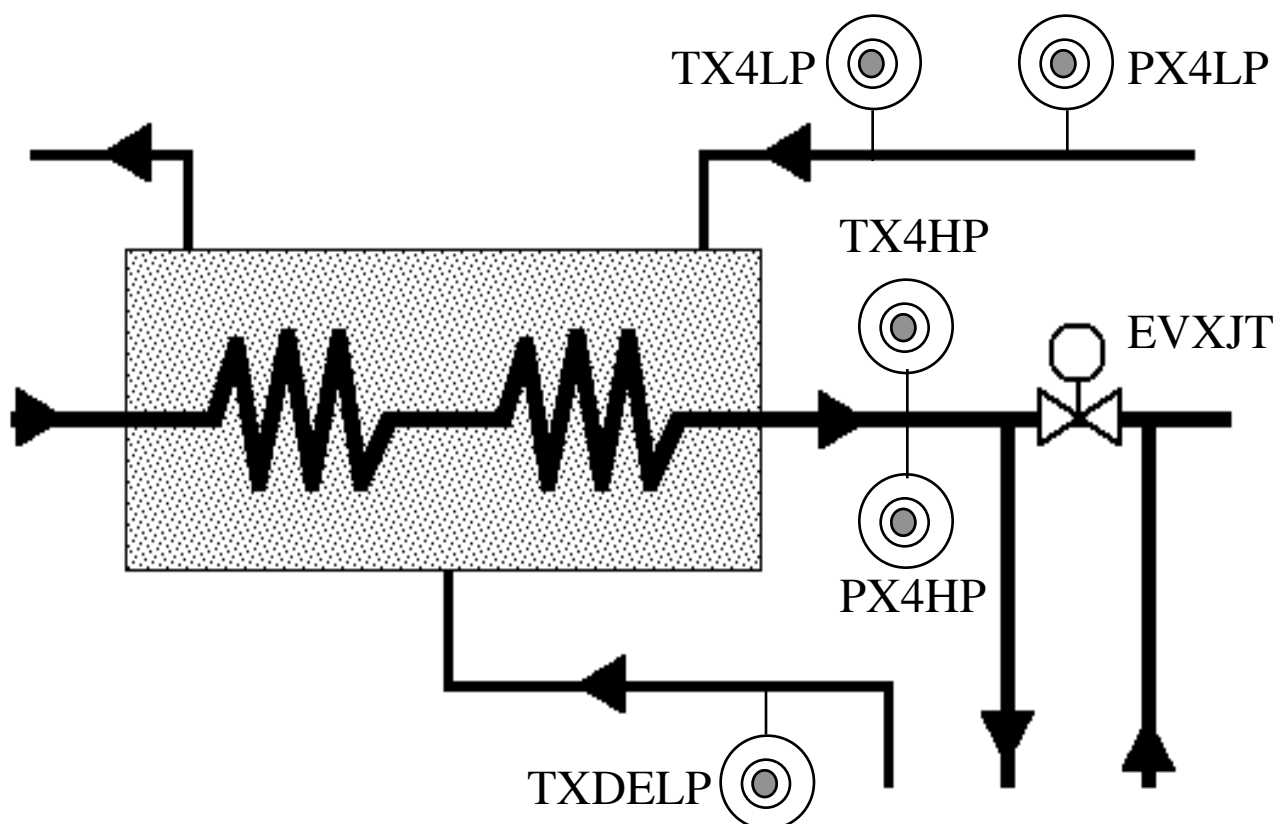
TX3HP: This is a VPT charged with neon gas. It reads the exit gas temperature of the high-pressure helium stream before it enters the dry engine and HEX IV.

PX3HP: This is a "Setra" transducer with a 0-500 psig range. It reads the pressure of the helium supply stream as it exits HEX III and heads for the dry engine.

THE HEAT EXCHANGER, HEX IV

Return Flow to HEX III

Return Flow from Wet
Engine and System

JT Valve - Used
when Wet Engine
is Off

EVXJT

Supply
Stream
to
HEX IV

Wet
Engine
Supply
and
Return
Flow

Return Flow from
Dry Engine

This heat exchanger is also of the tube and shell counter flow design, but its operation is a bit more complicated than the other heat exchangers. Cold gas from the dry engine directly enters the shell side of this exchanger. You may also find liquid helium entering the shell side of this exchanger from the wet engine, the system, or both.

EVXJT: This is a Joule-Thomson valve. It is specifically a one half inch Cryolab globe style valve with a Cv of .32. Typically, this valve is closed during normal operation.

INSTRUMENTATION for HEX IV

TX4LP: This is a VPT charged with helium gas. It reads the return flow gas temperature entering the shell side of HEX IV.

PX4LP: This is a pressure transducer, which reads the shell side pressure of HEX IV.

TX4HP: This is a VPT charged with helium gas. It reads the temperature of the gas leaving HEX IV before it goes to the wet engine.

PX4HP: This is a 0-500 psig pressure transducer, which reads the pressure of the gas leaving HEX IV before it goes to the wet engine.

TXDELP: This is a VPT charged with hydrogen gas. It reads the temperature of the gas flow coming from the dry engine.

DEWAR, VALVES, and JUNCTION BOX

A dewar is a vacuum-jacketed vessel used as a reservoir for any cryogenic liquid. The External Beamline's refrigerators use its helium dewars as a phase separator as well as a reservoir. The return flow of helium, from either the magnets or the bypass valve EVJBBY, enters the dewar and separates into liquid and gas.

The junction box is the point where the magnet string is attached to the refrigerator. Single phase helium flows from the junction box, through the transfer line to the magnet string, and then returns, as two-phase, to the junction box. (Cold gas can and does pass through the magnet strings, but generally this is only during cool down. Magnet operation requires liquid helium to obtain superconductivity.) The junction box accommodates the two-phase return from the magnet string to the refrigerator. It also houses the valve EVJBBY and a sub-cooler.
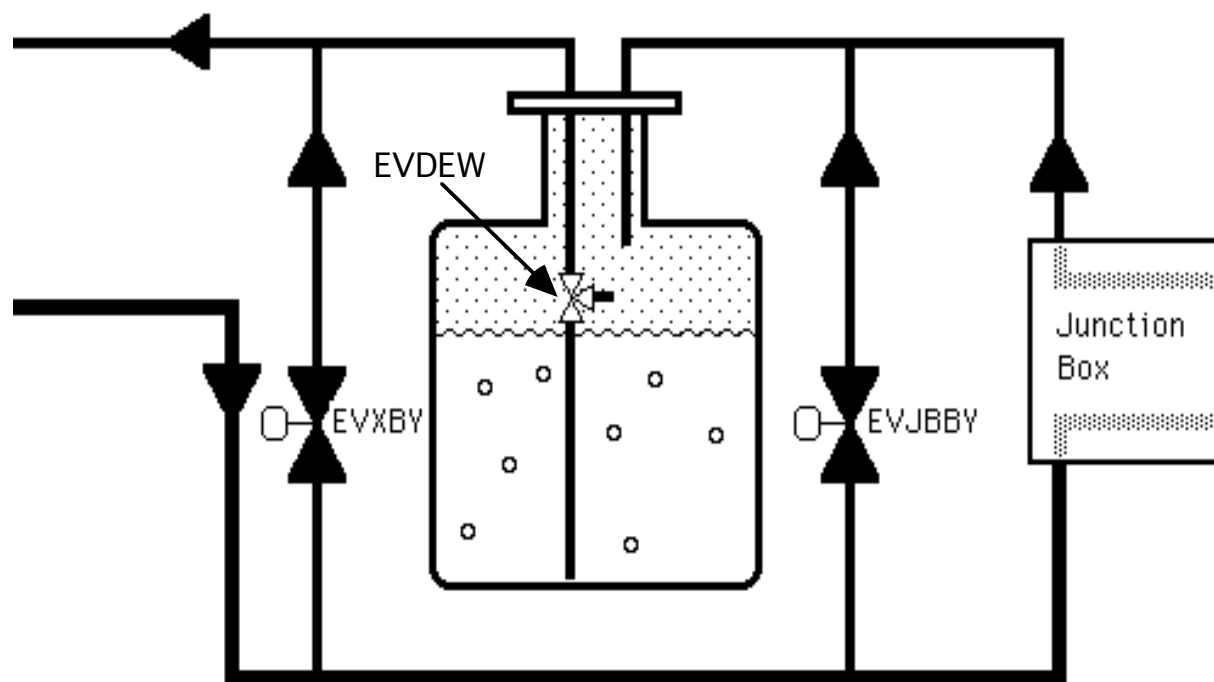
EVXBY: This valve has a Cv of 1.8 and is used as a transfer line pressure control valve. During cool down, it can be used shorten the loop by eliminating the dewar.

EVDEW: This is a full three-way valve. With the valve in the open position liquid is drawn from the bottom of the dewar. In the closed position it draws gas from the upper part of the dewar. During normal operation the valve allows the dewar to fill to about 78%.

EVJBBY: This is the bypass valve used to control the inlet temperature of the wet engine. It can also be used to fill the dewar or complete a loop for a test run of the refrigerator while isolating the magnet strings. It has a Cv of 3.3.

DEWAR INSTRUMENTATION
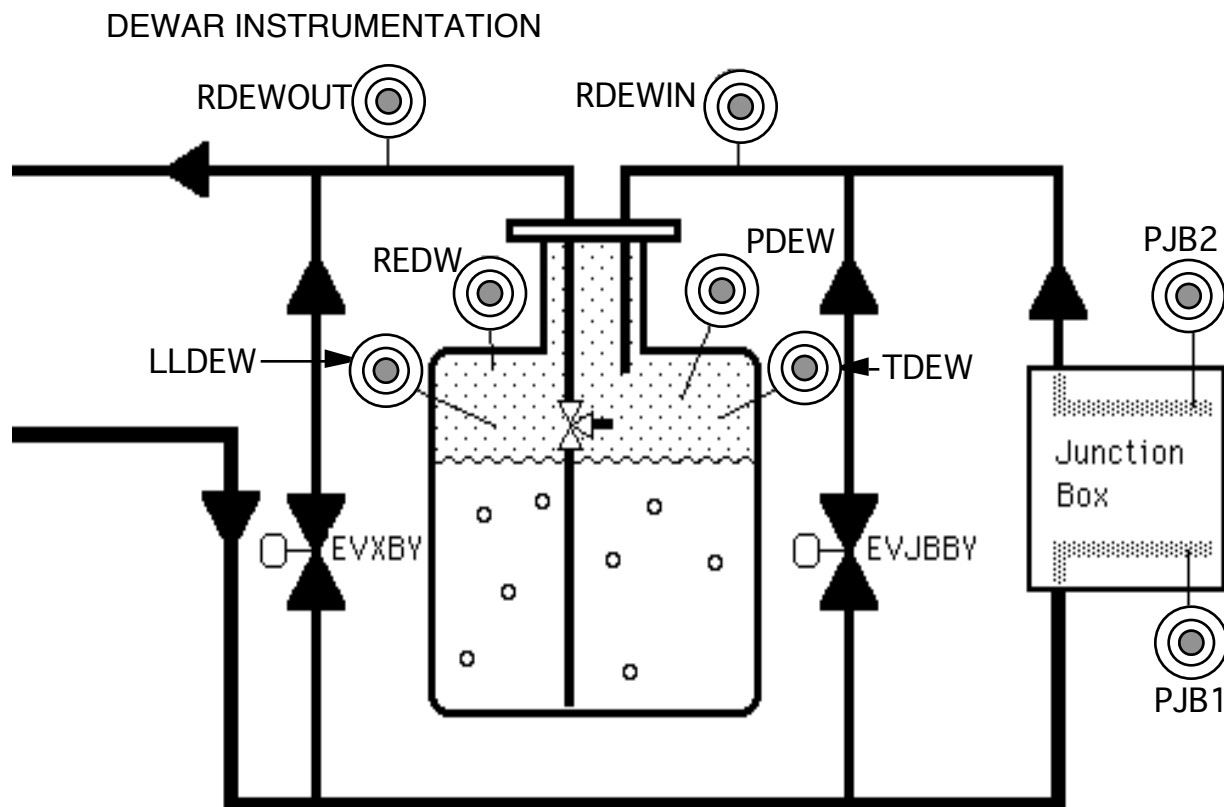
RDEWOUT: This is a carbon resistor mounted on a u-tube. It reads the temperature of the helium leaving the dewar.

RDEW: This is a carbon resistor located inside the dewar. It reads the dewar temperature.

LLDEW: This is an AMI probe, used to measure the liquid level in the dewar.

RDEWIN: This is a carbon resistor mounted on a u-tube. It reads the temperature of the helium entering the dewar.

PDEW: This is a Setra transducer. It reads the internal pressure of the dewar.

TDEW: This is a VPT charged with helium. It reads the temperature of the helium inside the dewar.

PJB1: This is a Setra transducer. It reads the supply pressure of the helium in the junction box.

TJB1: This is a helium VPT, which measure the temperature of the supply helium.

PJB2: This is a Setra transducer. It reads the return pressure of the helium in the junction box.

TJB2: This is a helium VPT, which measure the temperature of the return helium.

BLOCK & BLEED

The block and bleed panel is a manifold system of valves used to connect various parts of the refrigerator together. During cool down of the refrigerator, this panel is always used to help speed up the process.
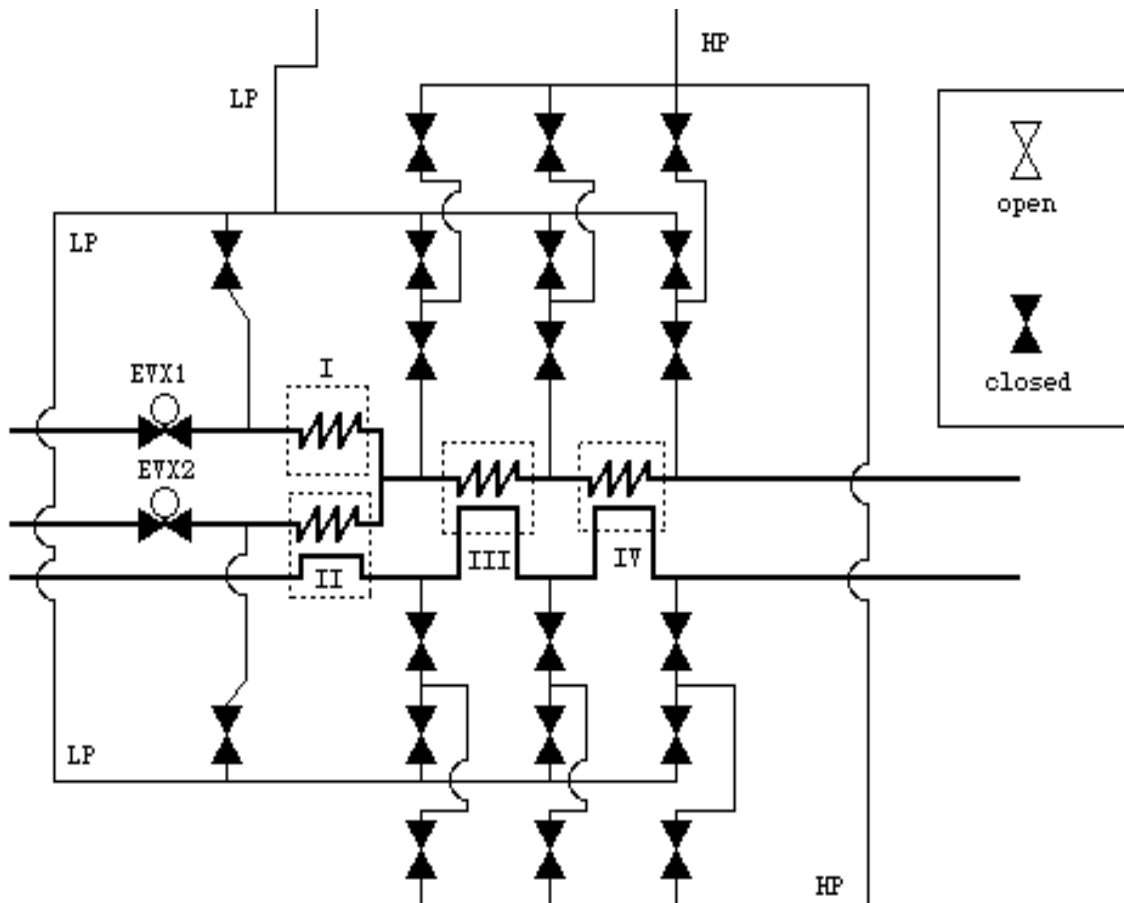
CLEANING THE SYSTEM

Before the following cool down process can begin, the system must be cleaned. Cleaning consists of flowing warm helium gas through each and every part of the system (compressor, heat exchanger, storage dewar, magnet strings) and also through an adsorber. This cleaning must lower the contamination level to below 5 ppm on an ARC cell.

COOL DOWN

Please note which of the following block and bleed valves are open and which are closed.
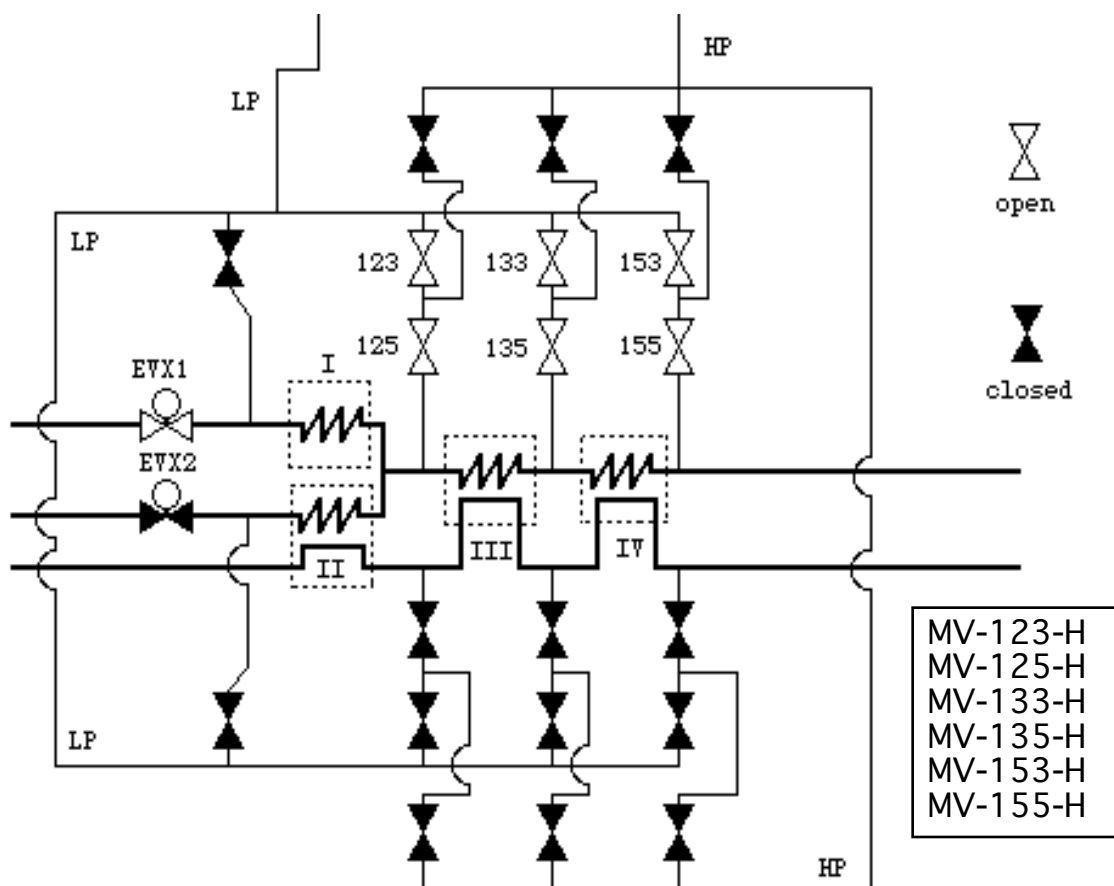
The cool down procedure states that these valves (listed in the bottom corner of the diagram) should be open and possibly throttled.

Valves **123** and **125** provide a single pass flow through HEX I, which aids in cooling the exchanger quickly. Throttling may be necessary to maintain stable suction pressure and to prevent relief valves from lifting. This portion of the procedure is the 300°K to 80°K transition. **IMPORTANT** - Once a heavy frost develops on these valves, they should be closed. This will direct more flow through HEX III.

Valves **133** and **135** provide a cool down path for HEX III. A heavy frost and proper instrument reading will dictate when to close these valves and direct more flow to HEX IV. The dry engine will be started when these valves are cold and are ready to be closed. This will establish a refrigerator flow path as well as begin the cool down of the shell sides of heat exchangers II and III.
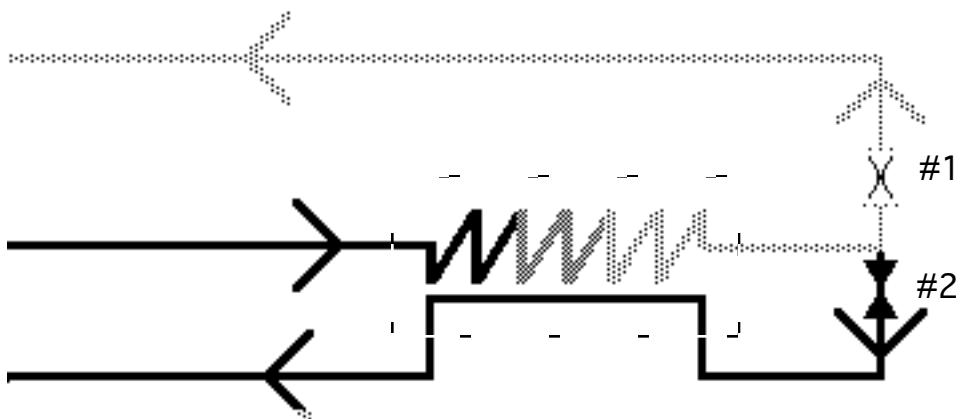
FLOW PATTERN

Why is single pass flow used?

Please look at the following diagrams and decide which of the two valves you would open to cool down this heat exchanger? Then think about why it might matter.
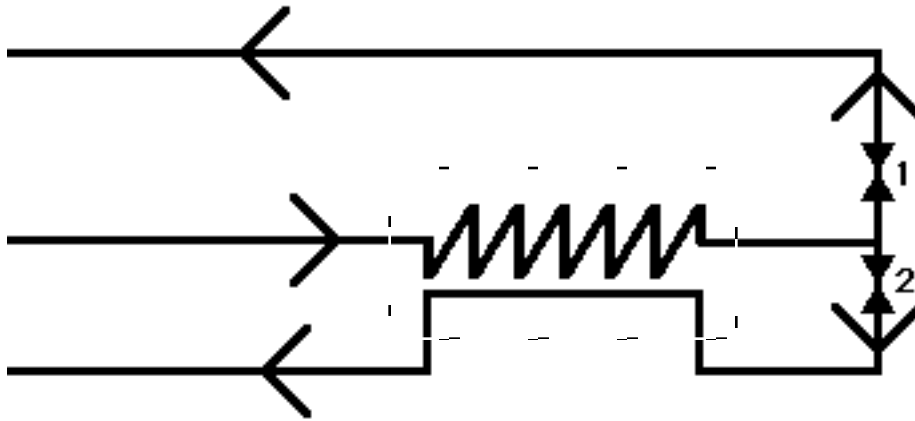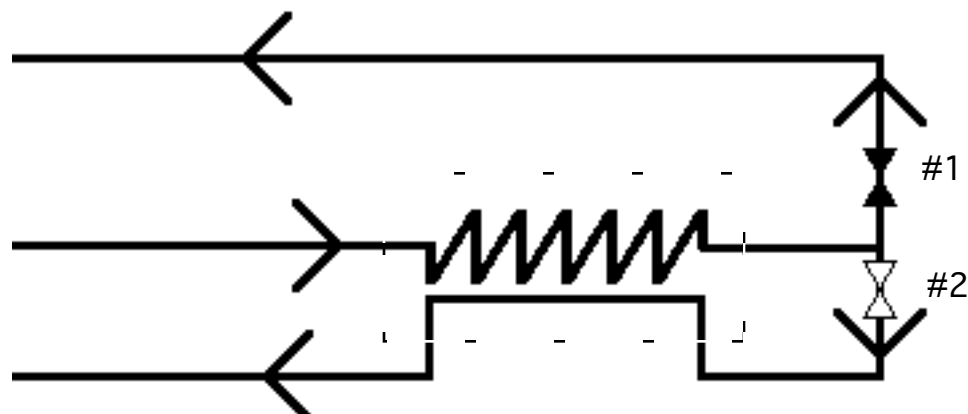
VALVE #1

Valve #1: Single pass flow is the proper method of cooling down the heat exchangers. When the tube side is cold the heat exchanger can be "turned." (This method of single pass flow can also turn a dewar.) The

term "turned" means that the supply flow of gas can give up its heat to the return flow — you don't have a heat exchanger until this is possible.

VALVE #2

Valve #2: Do you remember this formula, T° in = S° out   and   T° out = S° in? If you bring a warm gas through the return side, you will simply warm the supply side and the heat exchanger will stay one temperature throughout. In order for a heat exchanger to function properly there must be a differential in temperature — there must be a cold end as well as a warm end.

COOL DOWN PROCESS

The following diagrams and descriptions will show you the basic principles used to cool down a star refrigeration system.
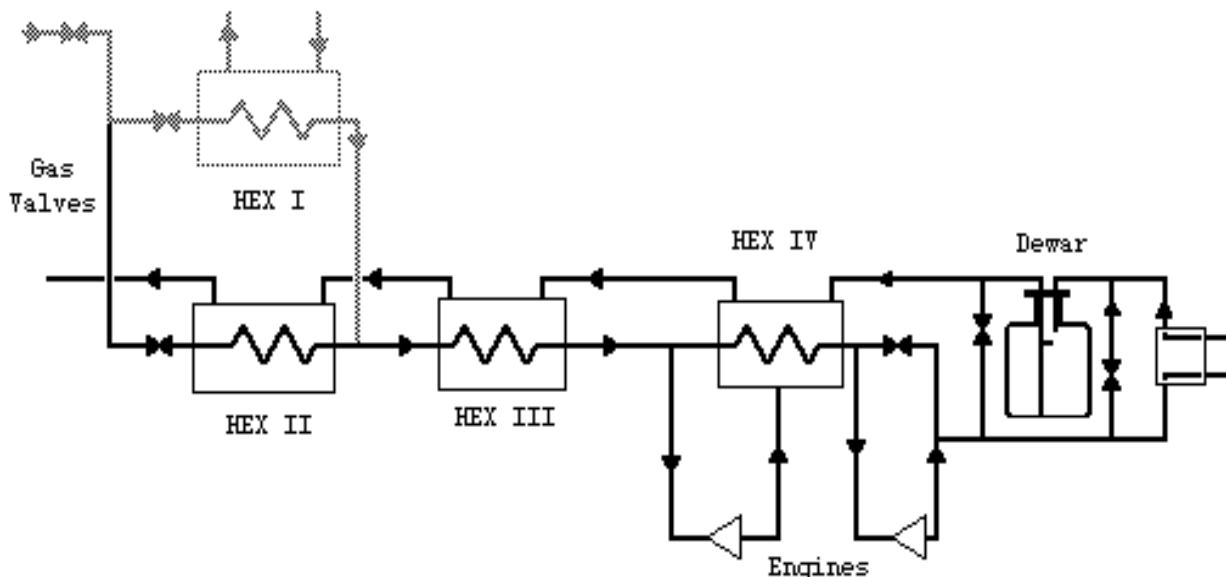

HEX I: The cool down process must start with HEX I and its flow of liquid nitrogen, which is used as the initial cooling fluid. The supply side stream of high-pressure helium gas reaches 80°K as a result of giving up its heat to the

liquid nitrogen flowing through the shell side. The block and bleed panel, valves 123 and 125, provides the helium gas a return path to the compressor.
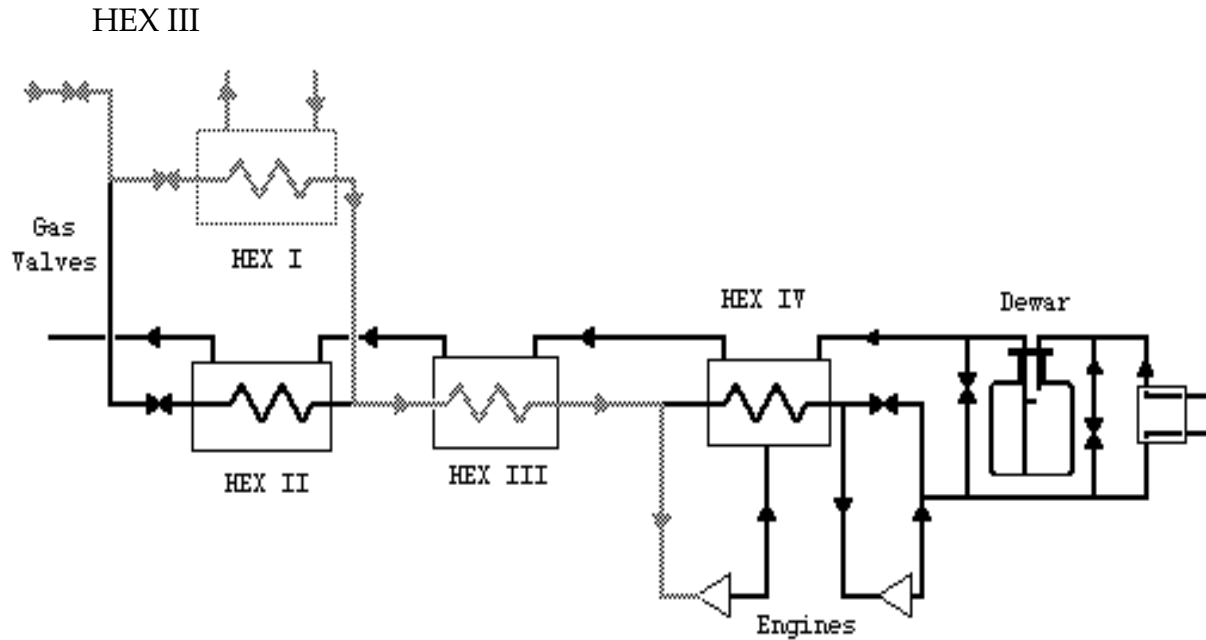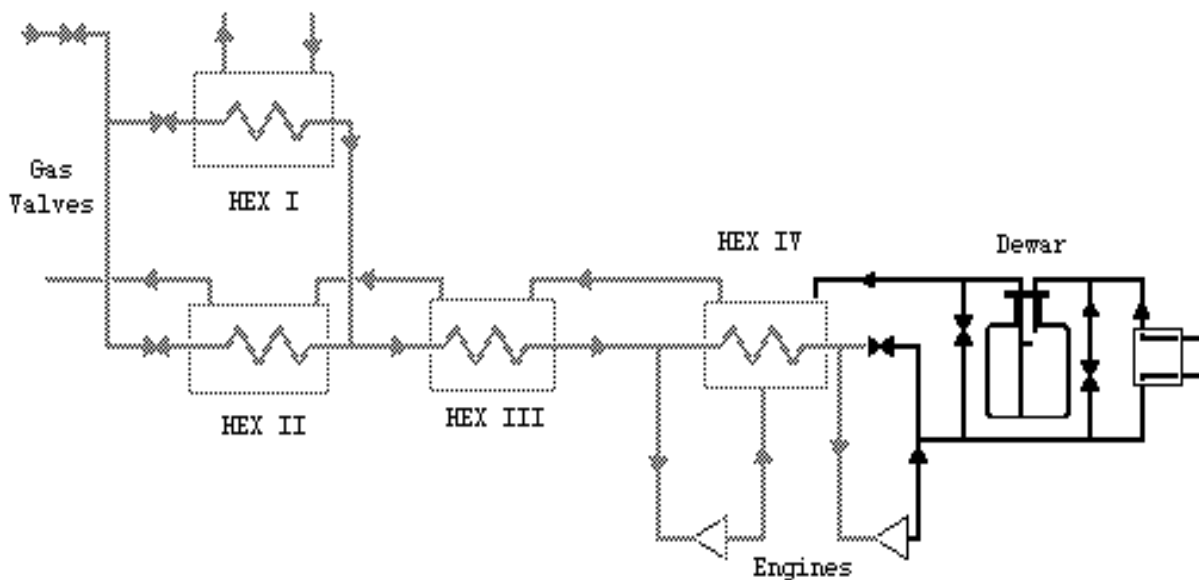
HEX III

The helium supply to HEX III can be cooled to <100°K by using valves 133 and 135 on the block and bleed panel.
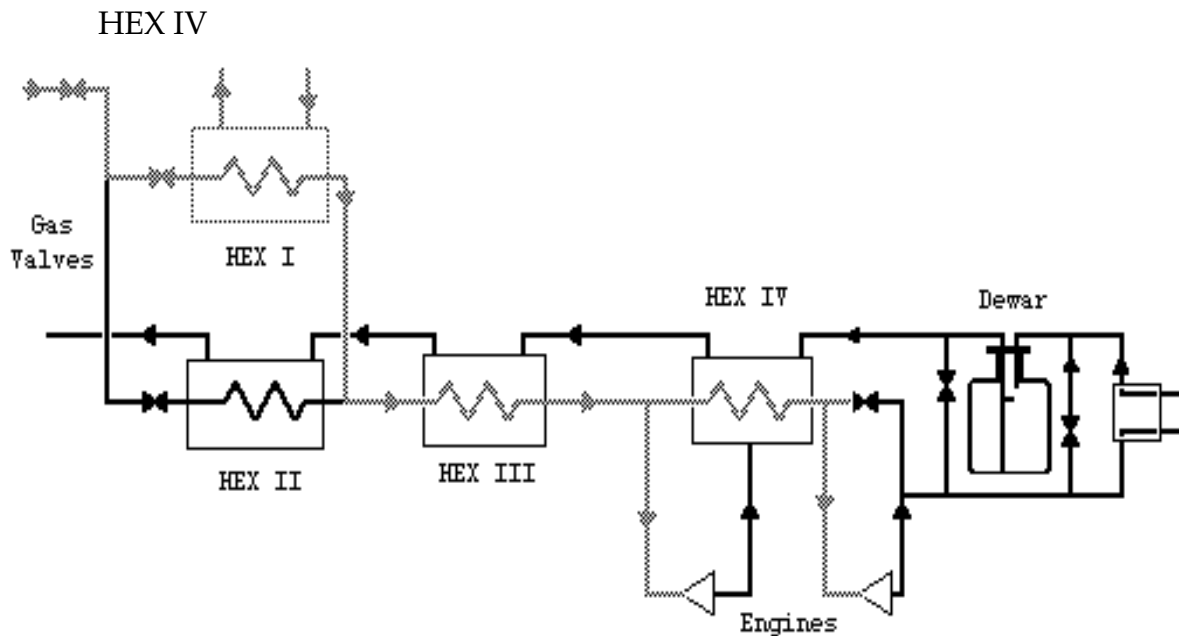
HEX IV

The helium supply to HEX IV can be cooled to <100°K by using valves 153 and 155 on the block and bleed panel.

### *DRY ENGINE*
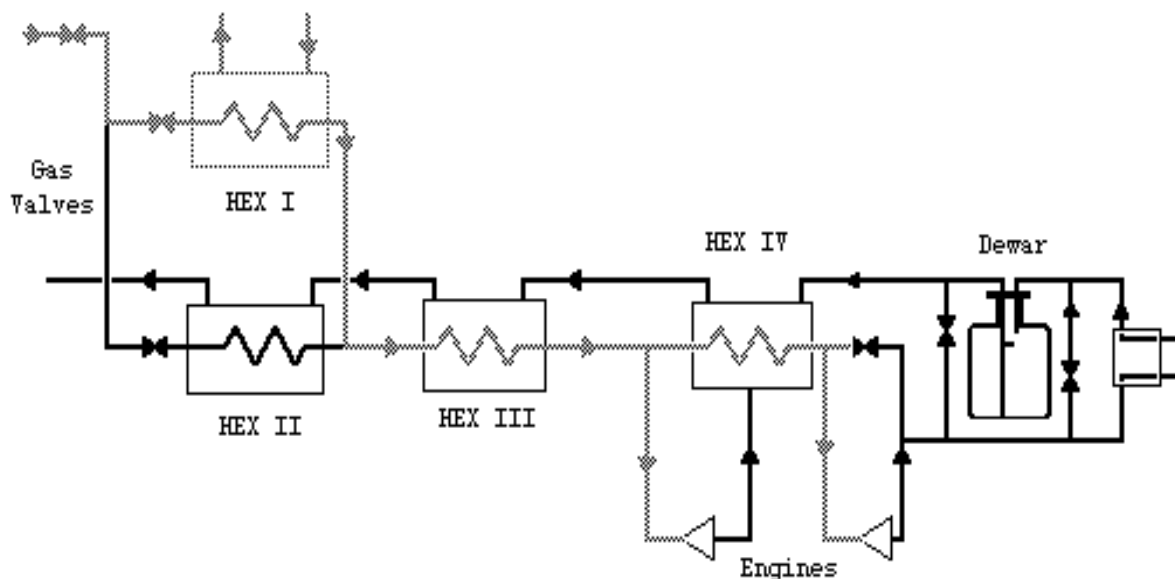
The dry engine can be started once the helium supply stream leaving HEX III is lower than 100°K. The dry engine will provide the necessary refrigeration to continue the cool down. The return flow will cool down the shell side of HEX II.
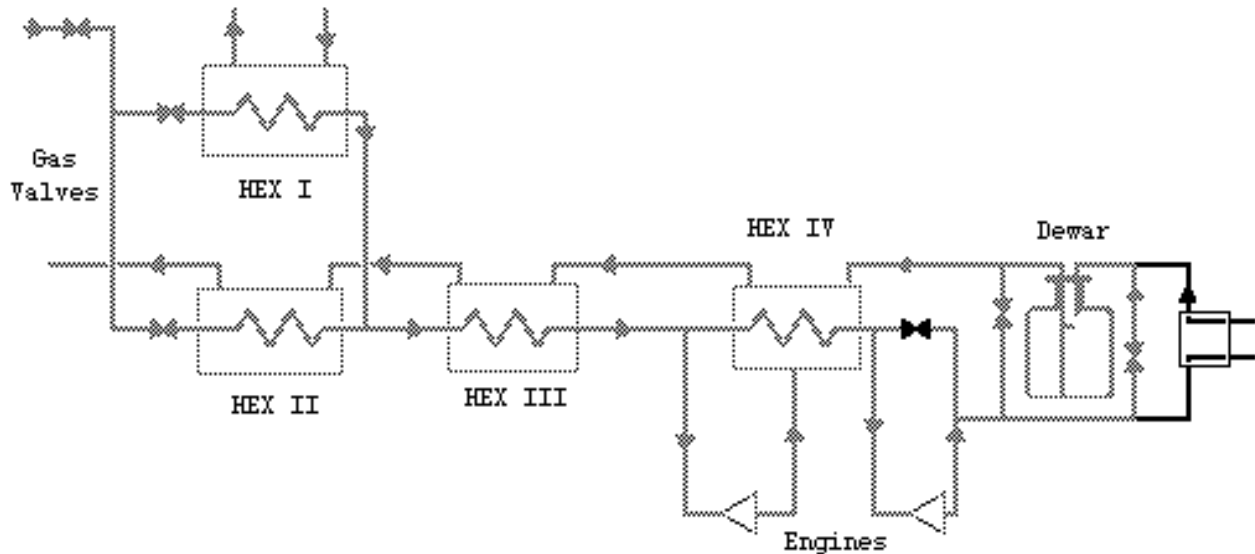
HEX II

Once the shell side of HEX II is cooled to <100°K, the valve EVX2 can be opened and the heat exchanger brought fully on line.

WET ENGINE
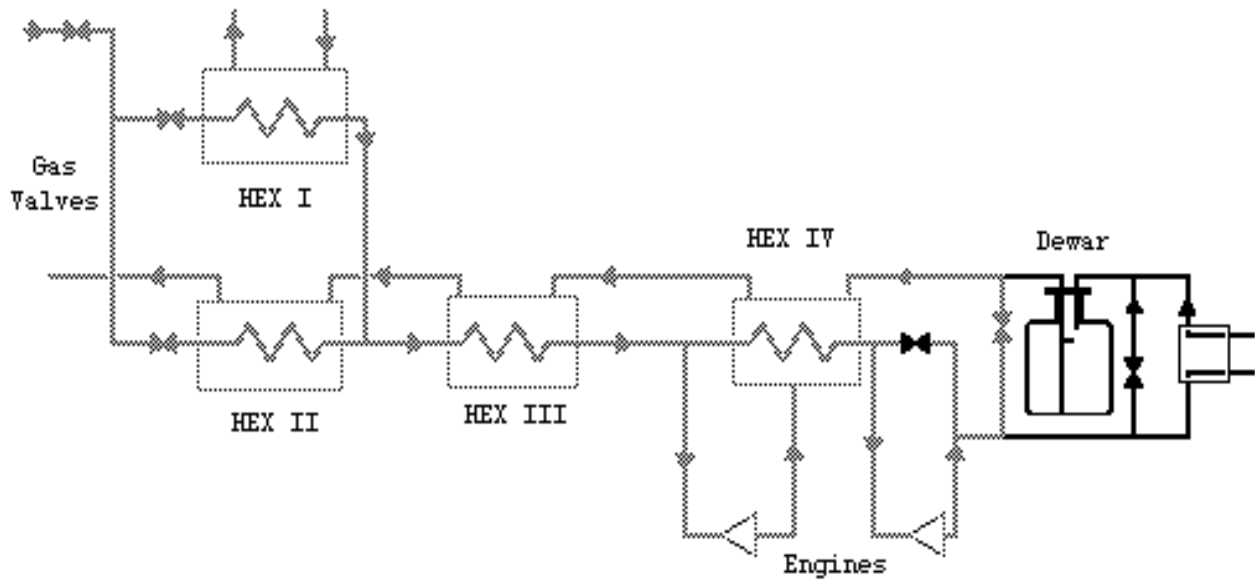
At this point, the wet engine can be started. The flow of liquid helium from the wet engine can be directed by EXVBY back through the shell sides of the heat exchanger, which aids in cooling.

DEWAR

The dewar can now be included in the refrigeration loop by valve EVJBBY, cooled down and filled. (A manual valve, 354, provides an initial cool down path for the dewar.)

The magnet strings, not pictured here, are cooled down in a similar way.

SCREW COMPRESSORS

This is the schematic symbol for a compressor. Notice the orientation of the triangle and the direction of flow through it.
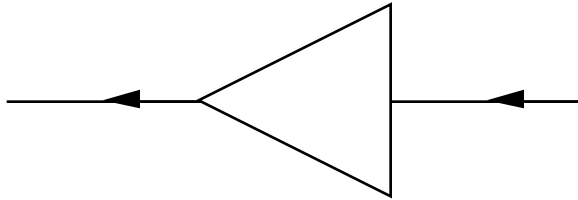
A compressor is a mechanical device that takes in gas at one pressure, generally low, and increases it to a higher pressure. The temperature of the gas increases as the pressure is increased. The compressor can also be considered as a flow device.

There are many types of compressors, reciprocating, centrifugal, diaphragm, and screw. The research department uses either the Mycom or the Sullair screw compressor.
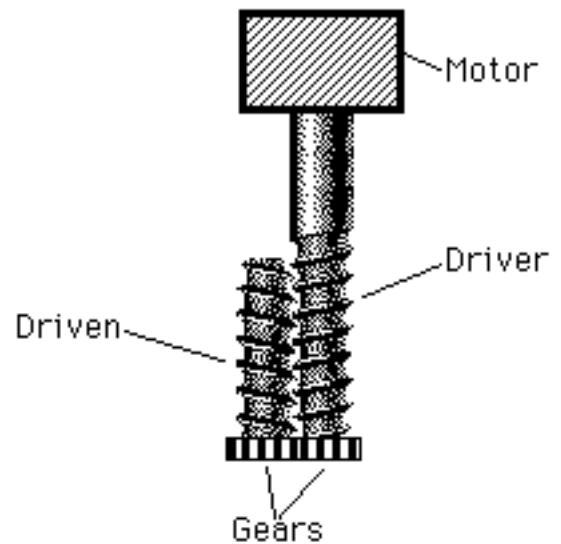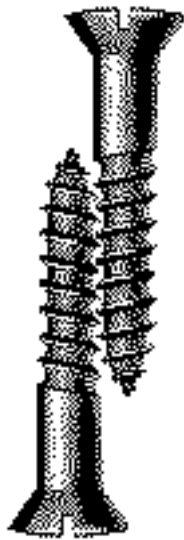
Screw compressors get their name because of the similarity they have with two screws meshed together. The gas is compressed as it passes through the meshing screw threads.

GLOSSARY

Absorbed-   Gas or vapor which has been taken up by molecular of chemical action.

Adsorbed-   Gas or vapor which has condensed on the surface as a layer.

Adsorber-   Traps and holds contaminates in the gas system. In the case of the Cryo system it's primary purpose is to remove all trace elements from the helium gas, principally nitrogen. An adsorber is used at the startup of the Cryo system to clean up the system and prevent plugging of the rest of the cryo equipment. For the same reason, an adsorber may be used at any time while the system is up and running if it is suspected that contaminants may be present.

Adsorbent- The material used in an adsorber to hold contaminants. Usual adsorbent is Silica-gel, Alumina, and Charcoal, with Charcoal being that which we use most. Characterized by coarse, high surface to volume ratio.

Atmosphere-   A convenient measure of pressure, 1 atmosphere is equal to 14.696 psia.   (psia- Pressure/Square Inch Absolute)

Carbon Resistor - A carbon resistor whose temperature sensitivity provides good temperature resolution, especially below 10° Kelvin. Carbon resistors are used in the helium equipment and are signified by the letter "R" in the device name giving the temperature readout. i.e.: BBT$\underline{R}$32. Carbon resistors used for this purpose are usually precision resistors at 100u range. They are calibrated by conditioning cards in the relay racks in junction with the device template in the programming.

Cold Box- Usually a low pressure vessel that provides vacuum insulation for the various connections to the heat exchanger.

Compressor- Screw compressor (oil flooded) used to compress helium gas from 1 psig (suction) to ~280 psig (discharge).

Control Dewar- A vacuum jacketed vessel used to store liquid helium and to maintain flow through a refrigerator.

Dry-Wet (Expansion Engines) - A device which removes energy from the helium gas which results in a drop of temperature and pressure. Normal operating temperatures of a dry engine are approximately 28°K in and 14K out.

Enthalpy- The sum (H) of the internal (U) and PV energy of a fluid of a given pressure and temperature.   (H = U + PV)

Entropy- The change in Entropy of a system is equal to the heat that it absorbs, divided by the absolute temperature. The Entropy of a substance is a derived thermodynamic quantity.

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Heat Exchanger- A device used to transfer heat from one substance to another.

Instruments- Devices that measure pressure, (PI), temperature, (TI), differential pressure indicator, (DPI), and alarms, (PA, TA).

Insulation- A means to reduce heat transfer by material means.

Insulating Vacuum- A vacuum provided for the express purpose of reducing conduction. The purpose is to prevent the absorption of heat into the cryogenic liquids, thus causing excessive flashing to gas or extra work on the refrigeration system.

Jacketed- A descriptive term used to signify cryogenic devices that have vacuum insulation provided. Thus the term Vacuum Jacketed, or more commonly, Jacketed.

J.T.- Abbreviation for the Joule-Thomson expansion valve. The J.T. valve can be used to replace the wet engine if needed, but has a much lower liquefaction rate. The J.T. valve takes high pressure gas on one side and releases it to the other side to remove energy and lower temperature. At low temperatures it is able to reduce energy enough to make a liquid and vapor solution.

Kelvin- The temperature scale that is used to signify absolute zero as zero degrees. Normal room temperature is ~300°K; normal superconducting operation is 4.7°K.

MWP (Maximum Working Pressure)- The maximum pressure a container, (dewar), should be operated

Pearlite- A finely divided powder used to insulate cryogenic storage devices, (dewars), when vacuum failure is a serious consideration, or the cost of super insulation would be too high.

Pressure- The force exerted per unit area. Dimensions are **p**ounds per **s**quare inch **a**bsolute- (**PSIA**), **p**ounds per **s**quare inch **g**auge- (**PSIG**), and **p**ounds per **s**quare inch **d**ifferential (**PSID**).

Quench - A situation where a small generation of heat in a superconducting magnet causes its flow of liquid helium to change to its gaseous state, causing the magnet to lose its superconducting ability.

Refrigeration- The extraction of heat at lower than ambient temperatures. The common name for a cryogenic system is "Refrigerator."

Relief Valve- There are two uses: 1- pressure relief, relieve pressure at M.W.P. + 10%, and 2- thermal, set to relieve at a pressure conveniently above system working pressure but below M.W.P.

Storage Dewar- A vacuum jacketed device used to store cryogenic fluids.

Transfer Line- A vacuum jacketed line used to move cryogenic fluids from one point to another.

Vacuum- Pressures below one atmosphere, 14.696 psia. Units of measurement are inches of mercury- (HG), Millimeters- (mm Hg). The most common reference in speaking about vacuum is Microns-(u Hg), and most common way of writing the form is 10^{x-n}.

Vapor- The gaseous phase of a material that is a solid or a liquid in its standard state at room temperature and atmospheric pressure.

Vaporizer- A device used to cause vaporization, that is, to cause liquid to change into its gas phase. Nitrogen dewars often have vaporizers which supply pressure to a nitrogen vessel in order to maintain working pressure. Also, the outlet side of a dewar is used to provide nitrogen gas to experiments or systems that are intended to use Gaseous nitrogen, (GN_2). (Some systems may use liquid nitrogen, these will not have a vaporizer on the outlet side of the dewar.)

Vapor Pressure- The pressure of the vapor of a liquid or solid at any given temperature at which the vapor and the liquid or solid phases exist in equilibrium.

Viscosity- The resistance to flow. Some cryogenic fluids have a very low viscosity.

V.P.T.- Vapor Pressure Thermometer. Its temperature limits are set by the expected temperature of the cryogenic gas measured. A hydrogen VPT would be used on the outlet of the dry engine. A neon VPT would be used on the inlet of the dry engine. A helium VPT would be used on the wet engine. VPT's are used in numerous locations throughout the cryogenic refrigerator. The VPT gets its name from the type of gas it is charged with. A very tedious calibration must be accomplished on each VPT each time it is charged. Due to its inherent nature, the VPT may loose part of its charge and frequently becomes unreliable. A good practice when using VPT's is to compare several in near locations to estimate their accuracy.

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